A New Dewpoint Pressure Correlation for Gas-Condensate Systems

by

Abdrabbalamir Abdallah Humoud

A Thesis Presented to the

FACULTY OF THE COLLEGE OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

PETROLEUM ENGINEERING

January, 2001

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

Bell & Howell Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

A New Dewpoint Pressure Correlation for Gas-condensate Systems

BY

ABDRABBALAMIR ABDALLAH HUMOUD

A Thesis Presented to the

DEANSHIP OF GRADUATE STUDIES

KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN, SAUDI ARABIA

In Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

In

PETROLEUM ENGINEERING

JANUARY 2001

Bell & Howell Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Mr. Abdrabbalamir Abdallah Humoud** under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN PETROLEUM ENGINEERING**.

Thesis Committee

M. A. Marhoun
Dr. Muhammad A. Al-Marhoun
Thesis Advisor

M. A. Aggour
Dr. Mohamed A. Aggour
Member

H. Y. al-Yousef
Dr. Hasan Y. Al-Yousef
Member

A. A. Almajed
Dr. Abdulaziz A. Al-Majed
Department Chairman

Dr. Osama A. Jannadi
Dean of Graduate Studies

Date: 21/01/2004

DEDICATION

To my mother and wife whose blessings and encouragement made this accomplishment possible

ACKNOWLEDGEMENT

Acknowledgement is due to King Fahd University of Petroleum and Minerals for the support of this research.

I wish to express my sincere appreciation and gratitude to Professor Muhammad A. Al-Marhoun, my thesis advisor, for his guidance throughout the course of this research. I would like also to thank the other committee members, Dr. Mohamed Aggour and Dr. Hasan Al-Yousef, for their comments and suggestions.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ملخص الرسالة

اسم الطالب الكامل : عبد رب الأمير عبدالله علي حمود

عنوان الرسالة : علاقة رياضية جديدة لحساب ضغط التكثف لمكثفات الغاز
التخصص : هندسة البترول
تاريخ التخرج : يناير ٢٠٠١ م

ان معرفة ضغط التكثف ضرورية جدا لوصف مكثفات الغاز ولتعيين فعالية مكامن مكثفات الغاز ولتصميم انظمة انتاجها. ان قياس ضغط التكثف في المختبر تعتبر عملية شاقة و مكلفة. لهذا تم في هذه الدراسة تطوير علاقة رياضية عملية جديدة عن طريق استخدام طرق تحاليل الاحصاء الانحسارية الخطية لتقدير ضغط التكثف لمكثفات الغاز. العلاقة الرياضية الجديدة تم تطويرها باستخدام ٧٤ مجموعة معلومات لمكثفات الغاز والتي تمثل مكامن مختلفة في منطقة الشرق الأوسط. العلاقة الرياضية الجديدة تربط بين ضغط التكثف لمكثفات الغاز وبعض العوامل التي يمكن الحصول عليها بسهولة. و لقد استخدم التحليل الاحصائي لتقييم العلاقات المنشورة والتأكد من دقة العلاقة الرياضية الجديدة. و لقد برهنت النتائج الاحصائية ان العلاقة الرياضية التي تم اشتقاقها في هذا البحث تفوق في الدقة و الأداء العلاقات الرياضية الموجودة.

درجة ماجستير العلوم

جامعة الملك فهد للبترول والمعادن

الظهران–المملكة العربية السعودية

يناير ٢٠٠١م

THESIS ABSTRACT

NAME OF STUDENT : Abdrabbalamir A. Humoud

TITLE OF STUDY : A New Dewpoint Pressure Correlation for Gas-condensate Systems

MAJOR FIELD : Petroleum Engineering

DATE OF DEGREE : January 2001

The knowledge of dewpoint pressure is essential for characterization of gas-condensate fluids, determination of gas-condensate reservoir performance, and design of production systems. Laboratory determination of the dewpoint pressure is usually laborious and costly. In this study, a new empirical correlation to predict dewpoint pressure of a gas-condensate system has been developed using multiple linear regression analysis. The new correlation was developed based on 74 data sets of gas-condensate systems representing different reservoirs in the Middle East region. The new correlation relates the dewpoint pressure to some readily available field parameters. Statistical error analysis, used to evaluate the existing published correlations and validate the new correlation, showed that the new empirically derived correlation outperforms the existing correlations.

MASTER OF SCIENCE DEGREE
KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
Dhahran, Saudi Arabia

January 2001

CHAPTER 1

CHAPTER 1

INTRODUCTION

A gas-condensate fluid is a natural hydrocarbon mixture that is predominantly gas and has a critical temperature lower than the reservoir temperature and cricondentherm temperature, which identifies a state on the dewpoint boundary, higher than the reservoir temperature. For gas-condensate fluids, the complete process of isothermal retrograde condensation upon the decrease of pressure at reservoir temperature involves the sequence of states; single phase, dewpoint, increase in quantity of the liquid phase to a maximum followed by decrease in the quantity to a second dewpoint, and finally the single phase sequence as relatively low pressures are reached. [9]

In any discussion of the dewpoint of hydrocarbon mixtures, it should be noted that there are two kinds of dewpoints that must be distinguished. The first type is the normal dewpoint, which occurs at low pressures as dry

gas is compressed to the point where liquid first forms. The second type, sometimes called the retrograde dewpoint, occurs when a gas mixture containing heavy hydrocarbons is depressured until a liquid is formed. The first type, as applied to gas-condensate mixtures, would normally be below atmospheric pressure and would be of no interest in reservoir performance. The second type is of great significance in reservoir and production engineering calculations. The determination of the gas-condensate dewpoint pressure is essential for characterization of gas-condensate fluids, determination of reservoir performance, and design of production systems.[6]

Ideally, the dewpoint pressure of a gas-condensate system is experimentally determined in the laboratory based on the visual reading of the liquid formation in a window-type pressure-volume-temperature (PVT) cell in a process called constant mass expansion (CME) test. This requires that the fluid samples of the primary-separator liquid and gas be obtained from a well, and they then be recombined according to the field measured gas-oil ratio (GOR) in order to experimentally determine the properties of the reservoir gas, including the dewpoint pressure.

As shown in the schematic diagram in Figure 1.1, the PVT cell is charged first with the gas by allowing the gas to expand into the cell and displace the mercury. The volume of the mercury displaced can be

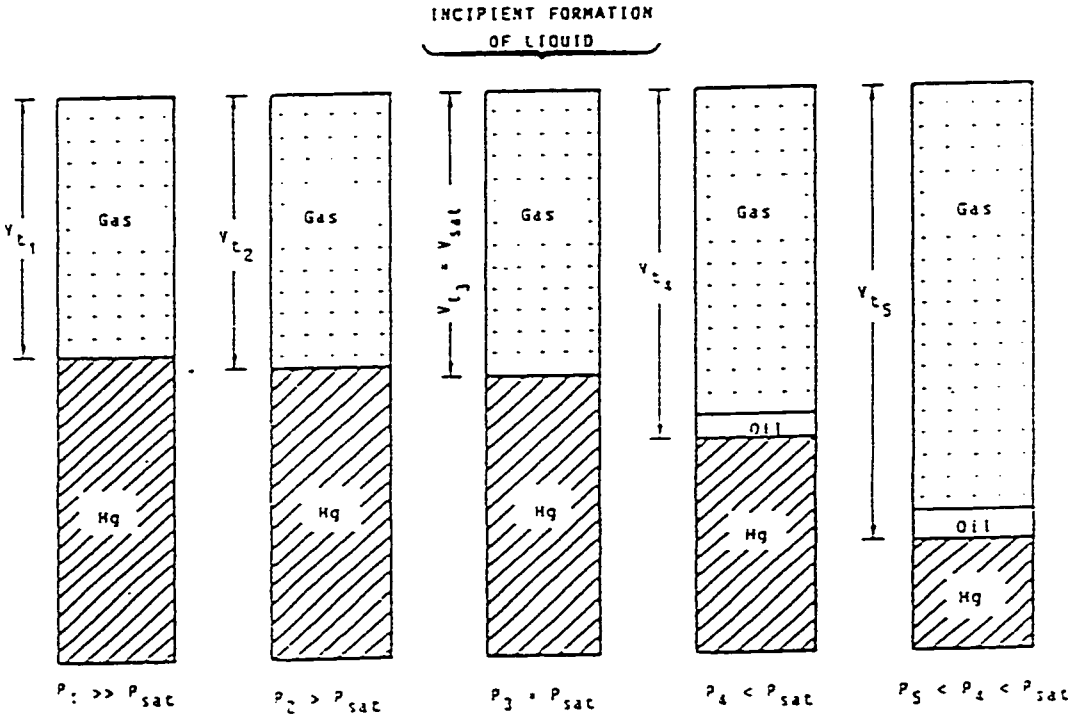

Figure 1.1: Schematic representation of CME experiment on a gas-condensate system. [13]

measured, and thus the volume of gas in the cell is known. Then, the recombined gas and liquid samples are added to the cell. The system in the PVT cell at reservoir temperature is compressed to a pressure above the recorded reservoir pressure. The cell is then left for equilibrium for some time. The total volume is recorded. The CME test is performed by reducing the pressure in a stepwise manner and visually observing the system. The dewpoint pressure is somewhat difficult to observe, and therefore the pressure reduction is continued below the dewpoint. The liquid volume is measured at each pressure. The data readings from the CME test are used to plot the liquid dropout curve as shown in Figure 1.2. It should be noted that the dewpoint pressure is obtained by extrapolating the liquid dropout curve.[13]

The laboratory measurement of the dewpoint pressure provides the most accurate and reliable determination. However, due to the following economical and technical reasons, quite often this information cannot be obtained from laboratory measurements: (1) the lab analysis might be expensive and cumbersome, (2) inability to obtain a representative sample, (3) sample volume is insufficient to obtain complete analysis, and (4) lab analyses are in error. In this case, the dewpoint pressure values must be predicted from empirically derived correlations.

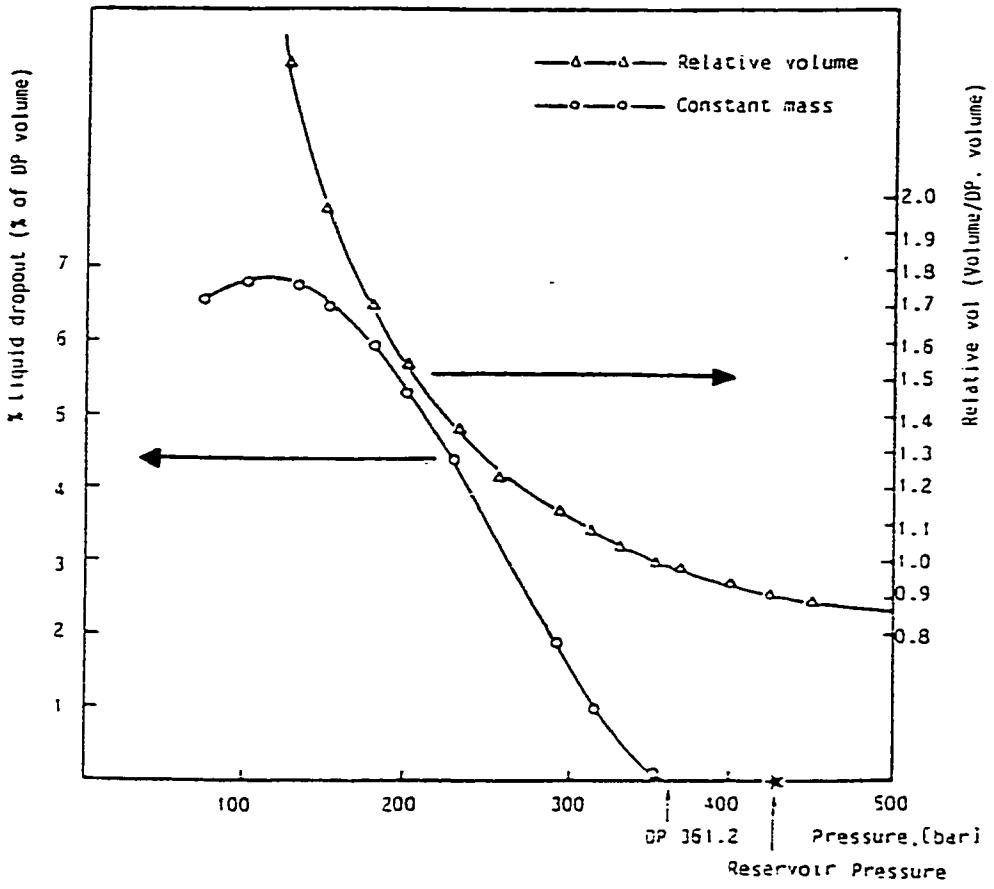

Figure 1.2: P-V and liquid dropout curves for a recombined gas-condensate sample at 121°C. [13]

The empirical correlations, proposed in different forms (mathematical expression, graphical, or tabulated) for determining the dewpoint pressures of gas-condensate systems, are considered very limited in the literature. In addition, these correlations were developed based on gas-condensate fluid samples obtained from certain reservoirs of specific regions of the world. Due to varying compositions of gas-condensate fluids from reservoirs of different regions, different empirical correlations may provide unacceptable predictions of dewpoint pressures when they are applied to gas-condensate fluids behaving differently from the fluid samples based on which they were developed. Most of these empirical correlations are strongly relating the dewpoint pressure to the gas-condensate fluid composition. Therefore, there is a great interest to evaluate the accuracy of these empirically derived correlations relative to the experimental dewpoint pressure values for the Middle East gas-condensate systems.

The objective of this thesis is to evaluate the existing gas-condensate dewpoint pressure correlations using unpublished experimentally obtained PVT fluid data representing Middle East gas-condensate reservoirs, and then develop a new empirical dewpoint pressure correlation to provide better dewpoint pressure predictions. The new correlation should depend only on readily available fluid properties normally measured in the field,

such as reservoir pressure and temperature, GOR, oil relative density, gas relative density, and possibly other easily obtained parameters.

Multiple linear/nonlinear least-squares regression analysis will be used to develop the new correlation. In addition, different statistical error analyses will be utilized to evaluate the new correlation against the existing empirical correlations in the literature using the experimental dewpoint pressure data utilized in developing the correlation. Furthermore, the new correlation will be validated using other experimental dewpoint pressure data sets not used in the correlation development.

CHAPTER 2

CHAPTER 2

LITERATURE REVIEW

2.1 Sage and Olds [3]

In 1947, Sage and Olds studied experimentally the behavior of five paired samples of oil and gas obtained from wells in San Joacuin fields in California. Their investigations resulted in developing a rough correlation relating the retrograde dewpoint pressure to the GOR, temperature and stock-tank API oil gravity. The results of this correlation were presented in tabulated form, Table 2.1, as well as in graphical form as shown in Figure 2.1 for the basis of 160°F. Similar diagrams were made for other temperatures and the same general relationships were noted in each case.

The results of this correlation indicated that this correlation is applicable only for GOR between 15,000-40,000 scf/STB, 100-220 °F, and for oil API gravity of 52°-64°. It should be emphasized that it is unlikely

Table 2.1: Relation of dewpoint pressure of California gas-condensate systems. [3]

Tank-oil gravity, °API	Gas-oil ratio, cu ft/bbl					
	15,000	20,000	25,000	30,000	35,000	40,000
			100°F			
52	4,440	4,140	3,880	3,680	3,530	3,420
54	4,190	3,920	3,710	3,540	3,410	3,310
56	3,970	3,730	3,540	3,390	3,280	3,180
58	3,720	3,540	3,380	3,250	3,140	3,060
60	3,460	3,340	3,220	3,100	3,010	2,930
62	3,290	3,190	3,070	2,970	2,880	2,800
64	3,080	3,010	2,920	2,840	2,770	2,700
			160°F			
52	4,760	4,530	4,270	4,060	3,890	3,650
54	4,400	4,170	3,950	3,760	3,610	3,490
56	4,090	3,890	3,690	3,520	3,380	3,270
58	3,840	3,650	3,470	3,320	3,200	3,110
60	3,610	3,430	3,280	3,150	3,040	2,960
62	3,390	3,240	3,100	2,990	2,890	2,810
64	3,190	3,060	2,930	2,820	2,740	2,670
			220°F			
54	4,410	4,230	4,050	3,890	3,750	3,620
56	3,990	3,780	3,600	3,440	3,300	3,180
58	3,700	3,480	3,280	3,110	2,970	2,850
60	3,430	3,210	3,030	2,880	2,760	2,660
62	3,150	2,970	2,800	2,670	2,570	2,480
64	2,900	2,740	2,590	2,470	2,380	2,300

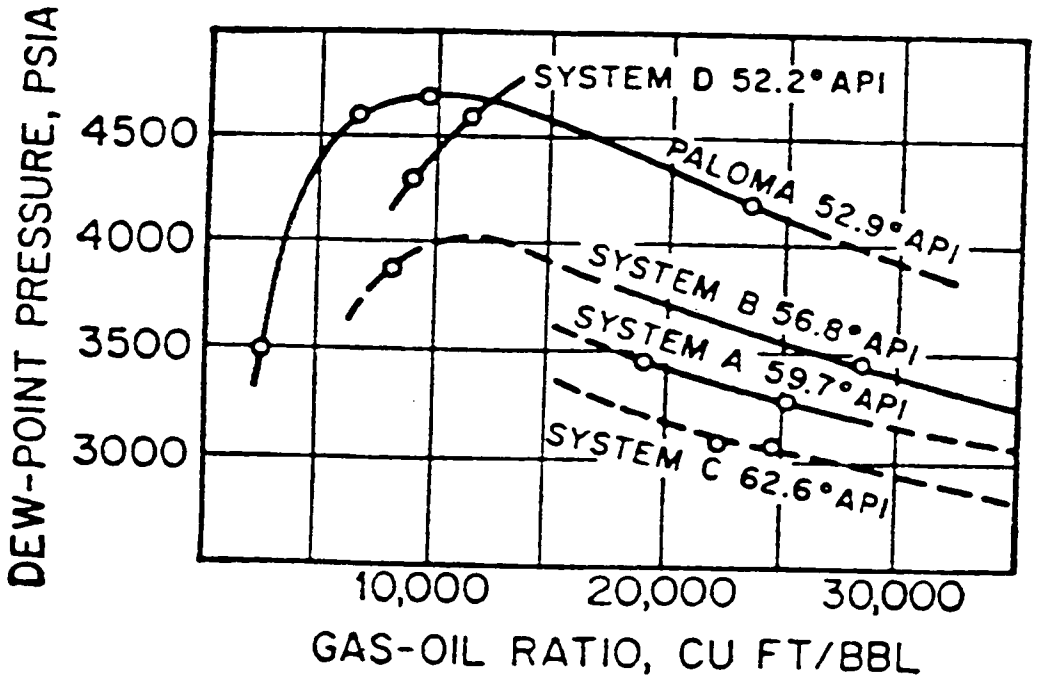

Figure 2.1: Influence of gas-oil-ratio and tank-oil gravity upon retrograde dewpoint pressure at 160° F. [3]

that the results presented in this study can be extrapolated with any reasonable degree of accuracy outside the ranges of GOR and tank API oil gravity. Consequently, this correlation is considered applicable only to the range of conditions covered in this study and for fluid systems of similar nature and compositions.

2.2 Reamer and Sage [4]

In 1950, Reamer and Sage conducted some experiments on five different pairs of oil and gas samples obtained from a field in Louisiana. They attempted to extend the existing correlation to higher GOR's. The measurements were made at GOR varied from approximately 200 to over 40,000 scf/STB, temperatures between 40° and 250° F, and the oil API gravities varied between 38° and 55.8°. Numerous diagrams depicting the effect of temperature and GOR upon the dewpoint pressure were presented. Some of these diagrams show that an isothermal increase in the GOR causes a decrease in the retrograde dewpoint pressure, and an increase in the temperature results in a decrease in the retrograde dewpoint pressure as shown in Figures 2.2 and 2.3. However, the influence of GOR and temperature on the dewpoint pressure was less pronounced for other cases as shown in Figures 2.4 and 2.5. They concluded that due to the complexity of retrograde systems, and the influence of composition on the volumetric

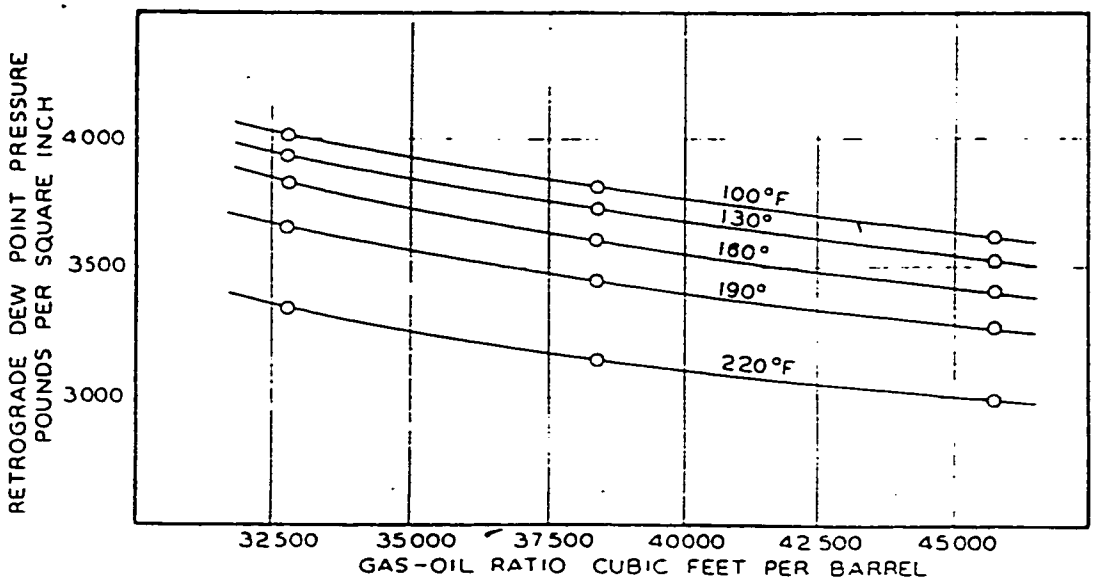

Figure 2.2: Influence of gas-oil-ratio upon retrograde dewpoint pressure of system E. [4]

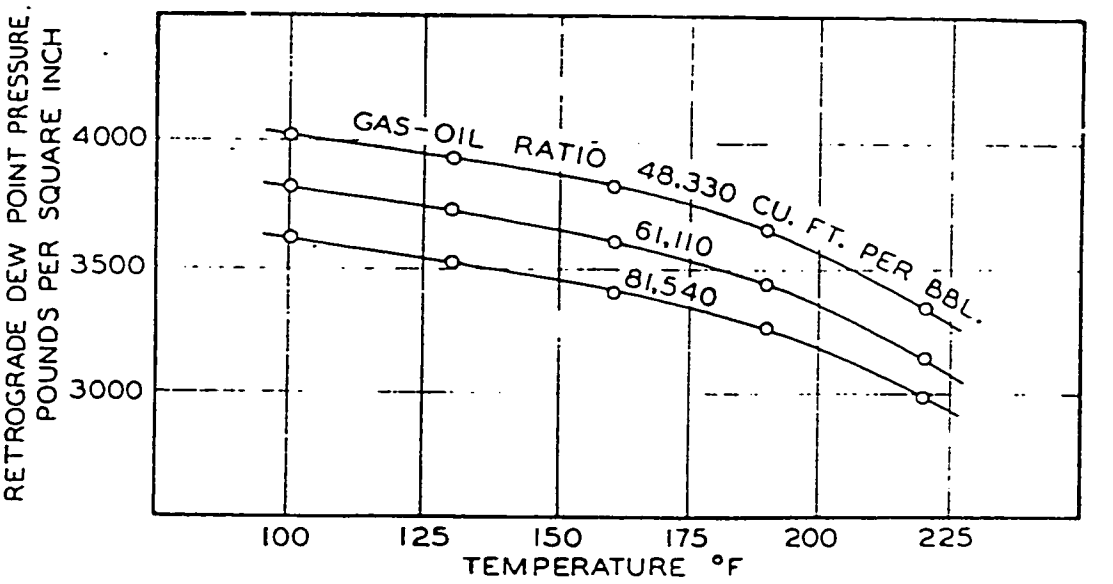

Figure 2.3: Influence of temperature upon retrograde dewpoint pressure of system E. [4]

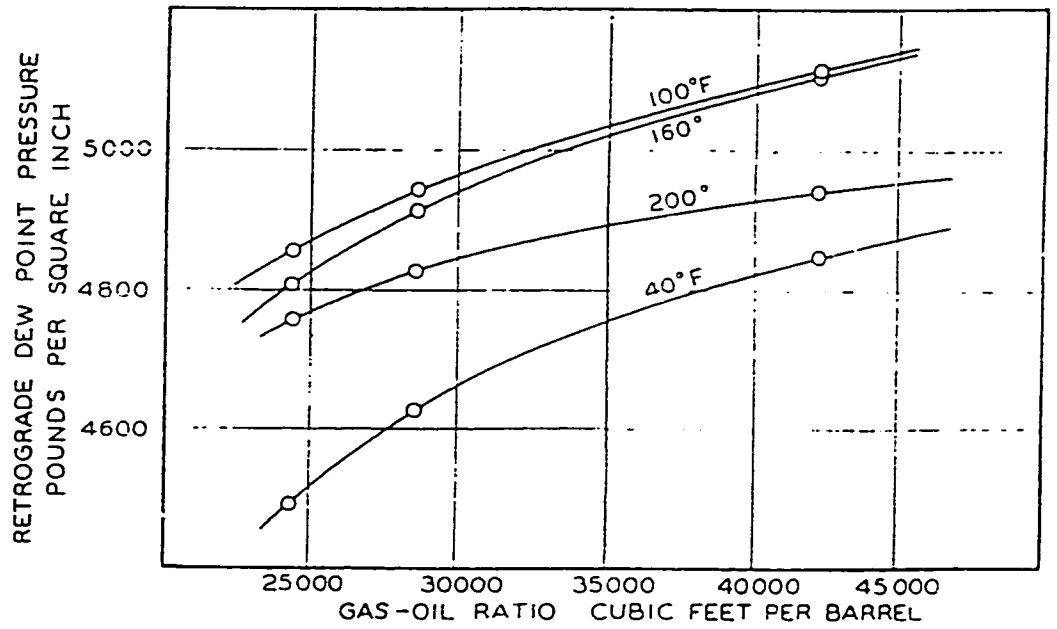

Figure 2.4: Influence of gas-oil-ratio upon retrograde dewpoint pressure of system A. [4]

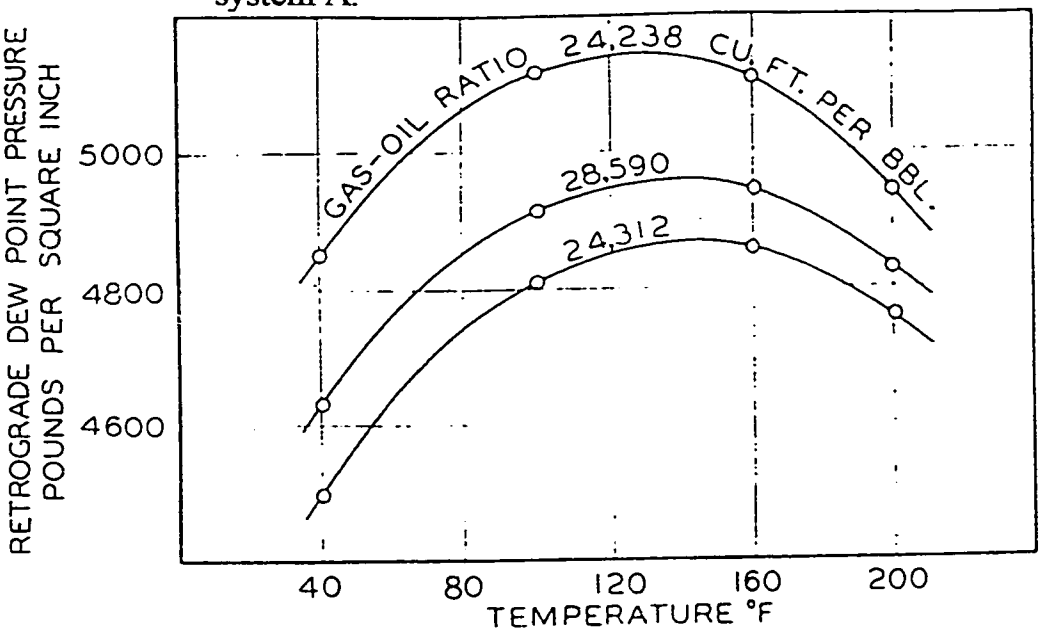

Figure 2.5: Influence of temperature upon retrograde dewpoint pressure of system A. [4]

phase behavior, it was doubtful that a useful correlation relating these variables could be established.

2.3 Organick and Golding [5]

In 1952, Organick and Golding presented a correlation for the prediction of saturation pressures, which could be a dewpoint or a bubble point pressure, for gas-condensate and volatile oil reservoir fluids. Saturation pressure is related directly to the chemical composition of the mixtures with the aid of two-generalized composition characteristics: (1) the molal average boiling point ($\overline{B}$) in °R, and (2) the modified average equivalent molecular weight (W_m), where

$$\overline{B} = \sum \text{(mol fraction)}_i.\text{(boiling point)}_i$$

$$W_m = \sum \text{(weight fraction)}_i.\text{(equivalent molecular weight)}_i$$

These parameters can be calculated from the composition of the mixture and the ASTM distillation on the heptanes-plus (C_{7+}). The W_m is a complex property to evaluate due to the existence of iso-paraffins and C_{7+}. The correlation was given in the form of 14 working charts, and on each chart the saturation pressure is plotted against temperature. Each value of

W_m gives a set of curves representing different values of $\overline{B}$ on each plot, See Figure 2.6. The other charts are given in Appendix B. The ranges of $\overline{B}$ and W_m covered in these charts are 210-380°R and 27.5-100 respectively. The comparison between experimental and predicted saturation pressure values of the 214 data points, which formed the basis for this correlation, revealed that the probable error of saturation pressure predictions is 5%. They also found that the probable error of the predicted saturation pressure values for the 119 data points of high GOR (greater than 40,000 scf/STB) gas-condensate fluids is about 8%. In order to clarify the procedures to be followed when applying this correlation, an actual illustrative example is given in Appendix B.

2.4 Nemeth and Kennedy [6]

In 1967, Nemeth and Kennedy developed a correlation relating the dewpoint pressure of a gas-condensate fluid to its chemical composition, temperature and characteristics of C_{7+}. This correlation was developed based on 579 data points obtained experimentally from 480 different gas-condensate systems. The dewpoint pressure and temperature ranges varied from 1,270-10,790 psi, and from 40-320°F respectively. A multiple regression analysis was used to develop this correlation. The final form of the equation as presented below contains eleven constants;

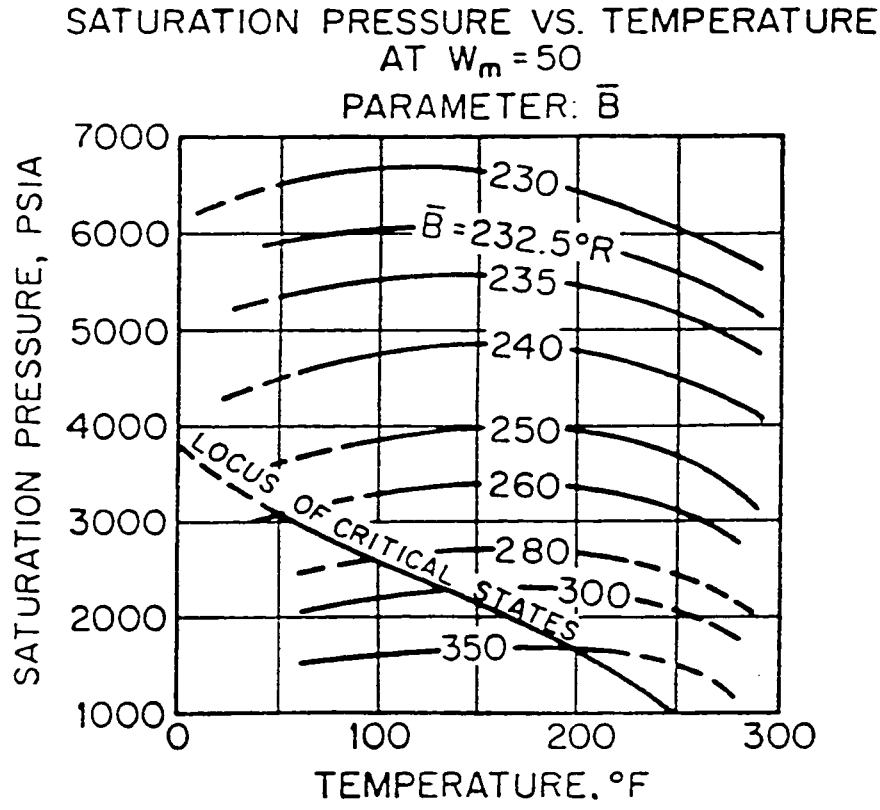

Figure 2.6: Saturation pressure versus temperature at $W_m = 50$. [5]

$$\ln P_d = A_1[y_{C2}+y_{CO2}+y_{H2S}+y_{C6}+2(y_{C3}+y_{C4})+y_{C5}+0.4y_{C1}+0.2y_{N2}]$$
$$+A_2\,\gamma_{C7+} + A_3[y_{C1}/(y_{C1}+0.002)] + A_4\,T + A_5(y_{C7+} \times M_{C7+})$$
$$+A_6(y_{C7+} \times M_{C7+})^2 + A_7(y_{C7+} \times M_{C7+})^3$$
$$+A_8[M_{C7+}/(\gamma_{C7+}+0.0001)]+ A_9[M_{C7+}/(\gamma_{C7+}+0.0001)]^2$$
$$+A_{10}[M_{C7+}/(\gamma_{C7+}+0.0001)]^3 + A_{11} \qquad (2.1)$$

where

P_d = dewpoint pressure, psia

y_{Ci} = mole fraction of component i in gas mixture composition

T = temperature, °R

γ_{C7+} = density of heptanes plus

M_{C7+} = molecular weight of heptanes plus fraction

$A_1 = -2.0623054$ $A_2 = 6.6259728$

$A_3 = -4.4670559 \times 10^{-3}$ $A_4 = 1.0448346 \times 10^{-4}$

$A_5 = 3.2673714 \times 10^{-2}$ $A_6 = -3.6453277 \times 10^{-3}$

$A_7 = 7.4299951 \times 10^{-5}$ $A_8 = -1.1381195 \times 10^{-1}$

$A_9 = 6.2476497 \times 10^{-4}$ $A_{10} = -1.0716866 \times 10^{-6}$

$A_{11} = 1.0746622 \times 10$

This correlation allows the calculation of the dewpoint pressure with an average absolute deviation of 7.4%, or 354 psi. Also, 50% of the data

points have a deviation of less than 6%, and 90% of data points have 15% deviation from experimental data.

2.5 Potsch and Braeuer [7]

In 1996, Potsch and Braeuer presented a graphical method for determining the dewpoint pressure as a backup for the laboratory visual reading of the total volume during a constant-composition expansion. The key idea of this method is to plot the number of moles, calculated as a function of single-phase compressibility factor (Z-factor), versus pressure. Above dewpoint pressure, the plot yields a straight line, and below dewpoint pressure the plot shows a curve. The point of intersection marks the dewpoint pressure, See Figure 2.7. It should be noted that a high accuracy (0.1%) single phase Z-factor calculation is necessary for this method to work.

Calculation of the dewpoint pressure is also possible by means of composition and K-values. The procedures used in this method usually involve trial-and-error process. The procedures are summarized below; [8]

1. Assume a trial value of dewpoint pressure. A good starting value can be obtained from Wilson's Equation.

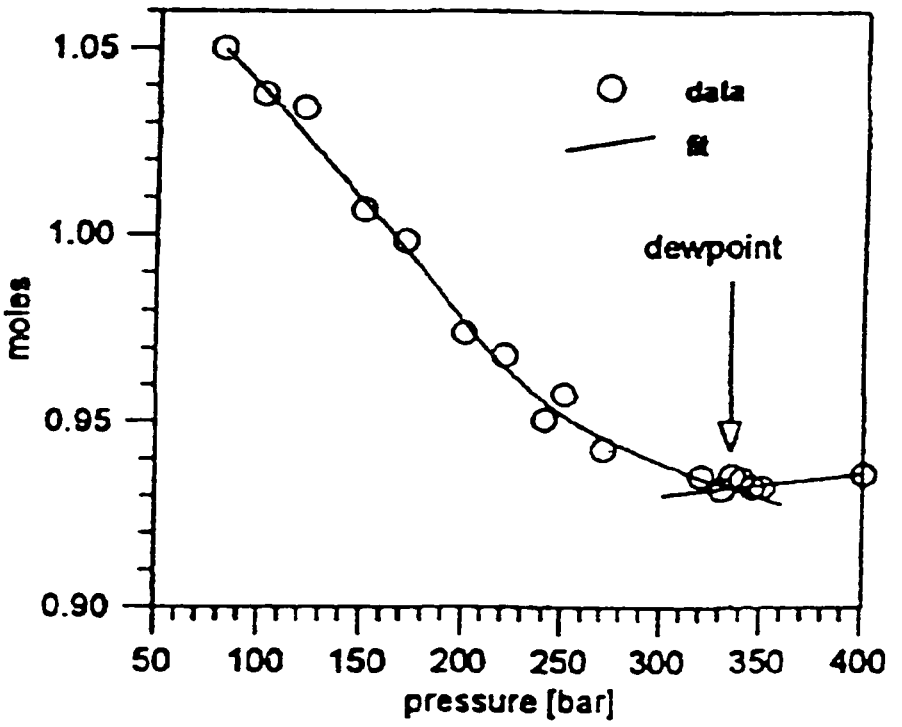

Figure 2.7: New technique for determination of the dewpoint via mole versus pressure. [7]

2. Calculate the K-value for each component at the assumed dewpoint pressure and system temperature.

3. Compute the $\sum_{i=1}^{n} \frac{Z_i}{K_i}$ for all components, where Z_i is the mole fraction of each component in composition.

4. If the $\sum_{i=1}^{n} \frac{Z_i}{K_i} \neq 1$, the dewpoint pressure is adjusted and procedures are repeated until the $\sum_{i=1}^{n} \frac{Z_i}{K_i} = 1$.

It should be noted that the dewpoint pressure is most sensitive to the smallest K-values, those of the heavy components, which are least accurately known. Thus, there is often more uncertainty in calculated values of the dewpoint pressure. [1]

CHAPTER 3

CHAPTER 3

REGRESSION AND STATISTICAL ANALYSIS

The fundamental concept of regression analysis is to fit a function of independent variables to a given set of data points in order to estimate or predict one dependent variable as accurately as possible. Regression deals with the nature of the relation between these variables. In evaluating the degree of regression, all the error or imprecision is assumed to be in the measurement of one variable called the "dependent", while the other variables are assumed to be precisely known. These precise variables are called the "independent" variables. If only one independent variable is involved then it is called simple regression analysis whereas the name multiple regression analysis is implied if more than one independent variable is present. The selected combination of independent variables is called a "model" which can be either linear or non-linear.

3.1 Linear Multiple Regression

In linear multiple regression, a linear function of independent

variables is selected as a model. The linear multiple regression is utilized to; (1) screen all variables and select the ones which have significant effect on the response, (2) obtain estimates of individual coefficients that structure the model, and (3) select the most effective prediction model.

A general multiple regression model, which relates a dependent variable y to k predictor independent variables, x_1, x_2, ..., x_k, is given by the model equation:

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_k x_k + e \tag{3.1}$$

where α and β's are coefficients to be determined by the regression analysis and e is a random error component. The estimated response, $\hat{y}$, is obtained from the sample regression equation:

$$\hat{y} = a + b_1 x_1 + b_2 x_2 + \cdots + b_k x_k \tag{3.2}$$

where each regression coefficient β_i is estimated by b_i from the sample data using the method of least-squares.

The errors or deviations between the observed and predicted values are assumed to have a zero mean and unknown variance. Also, it is assumed

that the errors are uncorrelated meaning that the value of one error does not depend on the other error. The n_k equations for the n_k experimental measurements can be expressed in matrix form as:

$$\begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1n} \\ 1 & x_{21} & x_{22} & \cdots & x_{2n} \\ . & x_{31} & x_{32} & \cdots & x_{3n} \\ . & . & . & . & . \\ . & . & . & . & . \\ . & . & . & . & . \\ 1 & x_{n_k 1} & x_{n_k 2} & \cdots & x_{n_k n} \end{bmatrix} \begin{bmatrix} \alpha \\ \beta_1 \\ \beta_2 \\ . \\ . \\ . \\ \beta_n \end{bmatrix} = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ . \\ . \\ . \\ y_{n_k} \end{bmatrix} \tag{3.3}$$

or in a simpler form

$$X\vec{a} = \vec{y} \tag{3.4}$$

where

$X = n_k \times (n+1)$ matrix

$\vec{a} = (n+1)$ vector, and

$\vec{y} = n_k$ vector, and

$n =$ total number of independent variables

Similar least-squares techniques can also be applied in estimating the coefficients when the linear model involves, for example, powers and products of the independent variables.

The least-squares estimators of the parameters $\alpha, \beta_1, \beta_2, \cdots, \beta_k$ are obtained by fitting the multiple linear regression model, Eq. (4.1) to the data points $x_{1i}, x_{2i}, \cdots, x_{ki}, y_i$; $i = 1,2,\cdots,n$ and $n > k$. y_i is the observed response. The curve that gives the best fit (least squares curve) to the data is the one that minimizes the sum of the squared deviations about that curve.

One measure that is commonly used to illustrate the adequacy of a fitted regression model is the coefficient of determination, or R-square (r^2). It is the proportion of variation in the experimental data that is explained by the fitted model. The closer the r^2 to the 100%, the more successful is the relationship in explaining this variation. The square root of r^2 is called the sample correlation coefficient (r).

3.2 Model Selection Methods

There are a number of model selection methods in the SAS statistical package used in this study. One standard procedure for searching the optimum subset of variables is a technique called "stepwise regression". It is

based on the procedure of sequentially introducing the variables into the model one at a time. The other two methods are the "forward selection" and "backward elimination". Forward selection starts with no variables in the model and adds variables one by one to the model. At each step, the added variable is the one that maximizes the fit of the model. Thus, variables are added one by one to the model until no remaining variable produces a significant F-statistic, or equivalently *t*-tests.

Backward elimination involves the same concepts as forward selection except that it starts with all the variables in the model and eliminates variables one by one from the model. At each step, the variable with the smallest contribution to the model is deleted.

Stepwise regression is accomplished with a slight, but important modification from the forward selection procedure. The modification involves further testing at each stage to ensure the continued effectiveness of variables that had been inserted into the model at an earlier stage. This represents an improvement over forward selection, since it is quite possible that a variable entering the regression equation at an early stage might have been rendered unimportant or redundant because of relationships that exist between it and other variables entering at later stages. Therefore, at a stage in which a new variable has been added to the regression equation through a significant increase in r^2, all the variables already in the model are subjected

to the *t*-tests and deleted if they do not show a significant value of *t*-test. The procedure is continued until a stage is reached in which no additional variables can be inserted or deleted.

3.3 Nonlinear Multiple Regression

The nonlinear regression is a procedure that produces least squares or weighted least square estimates of the parameters of a nonlinear model. Nonlinear models are usually more difficult to specify and estimate than linear models. The nonlinear procedure requires a model expression, parameter names, initial guess values of parameters, and derivatives of the model with respect to each parameter.

In some cases, the nonlinear models can be linearized or reduced to linear forms by applying the appropriate transformation of variables. For example, consider the following nonlinear equation:

$$Y = a \cdot X_1^{b_1} \cdot X_2^{b_2} \cdot e^{b_3 X_3} \tag{3.5}$$

Applying the logarithmic transformation on both sides, Eq. (3.5) can be re-written as:

$$\ln Y = \ln a + b_1 \ln X_1 + b_2 \ln X_2 + b_3 X_3 \tag{3.6}$$

which reduces to a linear equation that can be treated by the linear multiple regression method.

$$y = a' + b_1 x_1 + b_2 x_2 + b_3 x_3 \tag{3.7}$$

where

$$y = \ln(Y)$$
$$a' = \ln(a)$$
$$x_1 = \ln(X_1)$$
$$x_2 = \ln(X_2)$$
$$x_3 = X_3$$

3.4 Statistical Error Analysis

Statistical and graphical error analyses are used to check the accuracy and performance of the empirical correlation developed in this study. The accuracy of the correlation relative to the actual value is determined by using various statistical means. The criteria used in this study were average percent

relative error, average percent absolute relative error, minimum/maximum absolute percent relative error, the root mean square error, standard deviation, the correlation coefficient, and the *t*-test.

3.4.1 Average Percent Relative Error

This is a measure of deviation from the experimental data and is defined by:

$$E_r = (\frac{1}{n_d}) \sum_{i=1}^{n_d} E_i \tag{3.8}$$

E_i is the relative deviation in percent of an estimated value from a measured value and is defined by:

$$E_i = \frac{(x_{\exp} - x_{est})}{x_{\exp}} \cdot 100, \quad i = 1, 2, \ldots, n_d \tag{3.9}$$

where $x_{\exp}$ and x_{est} represent the experimental and estimated values respectively. E_r is an indication of the relative deviation in percent from the experimental values. The lower the value of E_r, the more equally distributed the errors are between the positive and negative values.

3.4.2 Average Absolute Percent Relative Error

It is defined as:

$$E_a = (\frac{1}{n_d}) \sum_{i=1}^{n_d} |E_i| \tag{3.10}$$

E_a indicates the relative absolute deviation, in percent, from the experimental values. A lower value implies a better correlation.

3.4.3 Minimum and Maximum Absolute Percent Relative Error

After calculating the absolute percent relative error for each data point, $|E_i|$, $i = 1, 2, \ldots n_d$, both the minimum and maximum values are found to determine the range of error for each correlation as follows:

$$E_{\min} = \min_{i=1}^{n_d} |E_i| \tag{3.11}$$

$$E_{\max} = \max_{i=1}^{n_d} |E_i| \tag{3.12}$$

Accuracy of a correlation can be examined by the maximum absolute percent relative error. The lower the value of the maximum absolute percent relative error, the higher is the accuracy of the correlation.

3.4.4 Standard Deviation

Standard deviation of the errors is a reflection of the dispersion of errors around the zero deviation and a measure of the quality of the fit. It is expressed as a positive square root of the variance (s^2);

$$s^2 = \frac{1}{n_d - 1}\sum_{i=1}^{n_d}(E_i - E_r)^2 \qquad (3.13)$$

A lower value of standard deviation means a smaller degree of scatter and a better quality of fit.

3.4.5 The Root Mean Square Error

It is another criteria to test the closeness of correlation prediction to the measured values and is defined as;

$$E_{rms} = \sqrt{\frac{\sum (E_i)^2}{n}} \tag{3.14}$$

The low value of E_{rms} indicates a good correlation. As the value goes higher, a worse fit is obtained.

3.4.6 The Correlation Coefficient

The correlation coefficient, r, represents the degree of success in reducing the standard deviation by regression analysis. The other term is the coefficient of determination, r^2, which is simply the square of the correlation coefficient (r) which is defined by:

$$r^2 = 1 - \frac{\sum_{i=1}^{n_d} (x_{\exp} - x_{est})_i^2}{\sum_{i=1}^{n_d} (x_{\exp} - \bar{x})_i^2} \tag{3.15}$$

where

$$\bar{x} = \frac{1}{n_d} \sum_{i=1}^{n_d} (x_{\exp})_i \tag{3.16}$$

The correlation coefficient lies between 0 and 1. A value of 1 indicates a perfect correlation whereas a value of 0 implies no correlation at all among the given variables. The larger the value of *r*, the greater is the reduction in the sum of squares of errors, and the stronger is the relationship between the independent variable and the dependent ones.

3.4.7 *t*-Statistic Test [20]

The *t*-test is a conventional statistic for measuring the significance of a difference of means. The significance is a numerical value between 0 and 1.0, and is the probability that $|t|$ could be this large or larger just by chance, for distributions with equal means. Therefore, when the probability is less than a small numerical value (i.e. < 0.001), the independent variable is considered significant in the model. The *t*-statistic is defined as:

$$t_j = \frac{b_j - \beta_j}{s_{D_j}} \tag{3.17}$$

where

b_j is the estimated parameter of each independent variable

β_j is the value stated in the null hypothesis (i,e $H_0 : \beta_j = 0$)

s_{Dj} is the standard error of each independent variable, estimated by:

$$s_{Dj} = \sqrt{\frac{\sum_{j=1}^{n}(Y_j - \hat{Y}_j)^2 /(n-2)}{\sum_{j=1}^{n}(X_j - \overline{X})^2}} \tag{3.18}$$

where $(Y_j - \hat{Y}_j)$ is the difference between the observed and estimated values of the dependent variable, and the $(X_j - \overline{X}_j)$ is the difference between the value of independent variable and the mean of values of that variable.

3.5 Graphical Error Analysis

Graphical means help in visualizing the accuracy of a correlation. Three graphical analysis techniques were used and presented below.

3.5.1 Crossplot

A crossplot is a plot of one variable obtained by two different means. A 45-degree straight line is drawn to reflect the perfect correlation line on which the estimated and measured are equal. Then, The estimated values are

plotted versus their corresponding measured values to form the crossplot. The closer the plotted data points to the perfect 45-degree line, the better the correlation is.

3.5.2 Error Distribution Analysis

This analysis shows error distribution histograms with overlaid normal-distribution curve of the correlation. It graphically shows the range of the error and at which the peak occurs indicating the adequacy of the prediction and the level of the correlation overestimation or underestimation.

3.5.3 Sensitivity Analysis

Sensitivity analysis is run to determine the influence of each independent variable on the dependent variable. Two types of sensitivity analysis will be studied. In the first type, each of the independent variables will be plotted against the dependent variable while the others are held constant. The plot will show the influence of the variable in different ranges. The influence of the variable to the correlation could be significant in a specific range while its influence is less significant in other ranges. The degree of influence will be indicated by the slope of the plotted points. If the

absolute slope is low, indicating a slight change in the dependent variable value as a result of a big change in the independent, the effect of that variable in the final correlation is small. The sensitivity of the dependent variable to the independent variable will be very significant if the plot shows a high slope. A horizontal line with a zero slope indicates a negligible effect.

The sensitivity analysis can also be investigated using categorized data of independent variables. In this type of analysis, the accuracy of any correlations will be plotted versus ranges of any independent variables and the number of data points will be indicated in each range or category. This is a useful analysis to check if the accuracy will be affected by the change in categories of independent variable or not.

CHAPTER 4

CHAPTER 4

DATA ACQUISITION AND DESCRIPTION

4.1 Data Acquisition

In developing an empirical model of the greatest value for predicting dewpoint pressures of gas-condensate systems, experimental data covering the widest possible range of conditions under which gas-condensate reservoirs occur are required. Also, unless the variables upon which the model is based are measured with relative ease, the usefulness of the correlation is decreased. Therefore, the main parameters that are readily measured should be the controlling factors in the new dewpoint pressure correlation.

Seventy-four (74) unpublished data sets, including the field production data and the results of constant mass expansion (CME) tests performed on gas-condensate fluid samples collected from the Middle East

region, were acquired and made available for this study. These data sets, which formed the basis of information for this study, were stored as data bank, and arranged in certain format to be readable by the SAS software package. Each data set included the reservoir pressure and temperature, the operating pressure and temperature of the primary separator, the primary separator gas-oil ratio, the separator gas specific gravity relative to air and the heptanes-plus specific gravity. Each data set included also the experimentally determined dewpoint pressure from CME test. The results of compositional analyses of all samples were utilized to estimate the pseudocritical properties of the gas-condensate systems. It should be noted that all the collected data were used without excluding or eliminating any data. Table 4.1 lists the ranges of the main parameters that were used to develop the new correlation, and the properties which characterize the Middle East gas-condensate systems.

4.2 Data Description

4.2.1 Dewpoint Pressure

All the collected dewpoint pressure data were experimentally determined from the constant mass expansion tests. The laboratory determination procedures for the dewpoint pressure were already covered in

Table 4.1: Ranges of gas-condensate production and PVT data

Property	Minimum	Mean	Maximum
Dewpoint pressure (psia)	2685	5469	7465
Reservoir pressure (psia)	2743	7384	8988
Reservoir temperature (°F)	100	233	309
Pseudoreduced pressure	4.2	11.5	14.4
Pseudoreduced temperature	1.30	1.71	2.18
Separator pressure (psia)	60	619	1215
Separator temperature (°F)	65	130	190
Gas-oil ratio (scf/SP bbl)	3,400	19,380	150,000
Separator gas specific gravity	0.66	0.7403	0.8199
Heptanes plus API gravity	42.4	45.9	55.9

Table 4.1 cont'd: Ranges of gas-condensate production and PVT data

Property	Minimum	Mean	Maximum
Reservoir gas specific gravity	0.7089	0.933	1.466
Gas FVF (res. cf/scf)	0.00260	0.00334	0.00506
Z-factor at res. pressure	0.807	1.257	1.591
N_2 (mole %)	3.07	9.31	18.3
CO_2 (mole %)	0.12	2.5	3.93
H_2S (mole %)	0	1.96	9.32
C_1 (mole %)	57.7	69.6	83.9
C_{7+} (mole %)	0.53	3.82	13.0

Chapter 1. Table 4.1 shows a wide range of dewpoint pressures. The minimum dewpoint pressure value is 2685 psia, which is close to the lower limit of 2500 psia below which the retrograde behavior will not normally be expected as mentioned in Appendix A. The maximum dewpoint pressure was found to be 7465 psia.

4.2.2 Reservoir Pressure and Temperature

The static bottomhole pressure and temperature of gas wells are routinely measured to monitor the well and reservoir performance. In this study, the static bottomhole pressure and temperature were considered important variables that thought to be well correlated with the dewpoint pressure. They are normally the closest conditions to the actual reservoir pressure and temperature. As noted in Table 4.1, a wide range of temperatures was covered in the data sets. It should be noted that the lower temperatures of gas-condensate reservoirs will not normally drop below approximately 200°F. Table 4.1 showed a minimum temperature of 100°F, which was achieved only in the laboratory as a part of phase relations study conducted on some samples at multiple temperatures including the reservoir temperature.

4.2.3 Gas-oil Ratio

Gas wells are individually tested by flowing their fluid streams through a two-phase, or three-phase if water exists, primary test separator to measure their production rates of gas and condensate fluids. The gas-oil ratio is calculated by dividing the gas rate corrected to standard conditions to the condensate rate measured at separator conditions, and the unit of GOR is scf/sep bbl. In addition, the operating pressure and temperature of the test separator are measured for correcting the GOR and other gas properties from the separator conditions to the standard conditions. As noted in Table 4.1, a very wide range of producing GOR's was covered in this study. The lower GOR limit falls close to the volatile-oil type upper GOR, and the upper GOR limit is considered extremely high for normal gas-condensate systems.

4.2.4 Gas and Heptanes-plus Specific Gravities

Gas and liquid separator samples are customarily collected from the primary separator during the production tests to determine both the separator gas specific gravity at separator conditions, and the heptanes-plus specific gravity and its molecular weight at standard conditions. Since the

condensate consists mostly of heptanes-plus, the API gravity of the heptanes-plus would be close to the condensate stock-tank API gravity. Table 4.1 shows that the range of heptanes-plus gravity is 42.2-55.9°API, and this falls within the stock-tank liquid gravities of gas-condensate fluids (40-60°API).

4.2.5 Pseudoreduced Pressure and Temperature

Since the behavior of gas-condensate mixtures is usually complex, the concept of gas pseudocritical properties was introduced in the dewpoint pressure correlation development. The pseudocritical pressure and temperature for each sample were estimated directly from the laboratory-determined compositional data using equations A.1 and A.2, discussed in Appendix A. It should be pointed out that the pseudocritical properties can also be predicted using some empirical correlations based on the reservoir gas specific gravity as discussed in Appendix A. The critical properties of the heptanes-plus were estimated using the correlations presented in equations A.8 through A.10. If the gas-condensate mixture contains non-hydrocarbon gases, then the pseudocritical properties should be corrected using equations A.5 through A.7. Then, equations A.3 and A.4 were used to determine the pseudoreduced pressure and temperature of each gas-condensate system.

4.3 Data Consistency

The Chevron Phase Calculation Program (CPCP), a PVT simulator based on equations of state, was used to check the consistency of the collected data. The field and laboratory data were utilized to build models for all gas-condensate systems considered in this study. These models were tuned to match the experimental dewpoint pressure value at reservoir temperature. Then, flash calculations were performed to determine the gas and liquid phase compositions, and to estimate the gas-oil ratio at the field-tested separator pressure and temperature. The results obtained from the simulator were compared with the field measured and laboratory analysis data to check the validity of these data. Additional parameters were obtained from the PVT simulator, such as the gas-oil ratio and the API gravity of condensate calculated at standard conditions. These parameters were attempted for correlation with the dewpoint pressure.

CHAPTER 5

CHAPTER 5

DEVELOPMENT OF THE DEWPOINT PRESSURE CORRELATION

5.1 Selection of the Independent Variables

Multiple least-square regression analysis was utilized to develop this new dewpoint pressure correlation. Statistical regression programs (RSQUARE and STEPWISE) were developed using SAS software package to build the models, investigate the behavior of many regression models and evaluate each combination of the dependent variable with the independent variables.

The first step in developing the correlation was to select the parameters that are anticipated to influence the dewpoint pressure behavior. Two types of independent variables were used to develop the new model. The first type of independent variables was based on the pressure and temperature

conditions, while the second type of independent variables was related to the gas-condensate fluid composition. The following parameters were considered in the development of the new correlation:

- Reservoir pressure (P_R)
- Reservoir temperature (T_R)
- Primary separator pressure (P_{SP})
- Primary separator temperature (T_{SP})
- Primary separator gas-oil ratio (R_{SP})
- Reservoir gas specific gravity (γ_{gR})
- Primary separator gas specific gravity (γ_{gSP})
- Heptanes-plus specific gravity (γ_{C7+})
- Heptanes-plus molecular weight (M_{C7+})
- Stock-tank API gravity
- Compressibility factor at reservoir condition (z)
- Formation volume factor (B_g)
- Concentrations of C1, C4, C7+ in composition
- Pseudocritical pressure (P_{pc})
- Pseudocritical temperature (T_{pc})

The relationship between the dewpoint pressure and the above parameters was studied based on graphical and statistical means. Figure 5.1

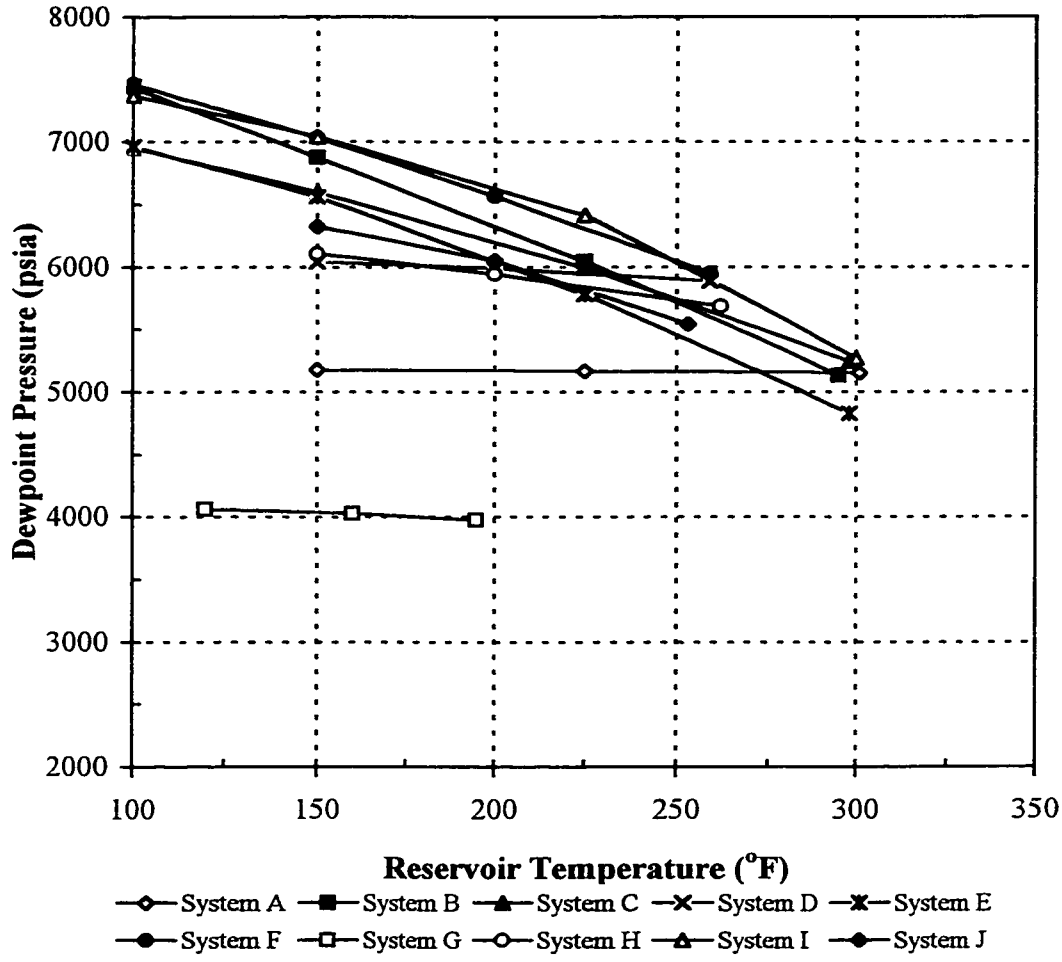

Figure 5.1 : Influence of reservoir temperature on the dewpoint pressure

is a sample graph showing the influence of the reservoir temperature on the dewpoint pressure for different gas-condensate systems. Different curves representing dewpoint lines of these systems are illustrated in this graph. The general trend of these curves shows that as the temperature increases the dewpoint pressure decreases. It is also observed in this graph that for some gas systems the variation in the dewpoint pressure due to the change in temperature is very small compared to other systems. Depending on the composition of each gas system, different systems may exhibit different dewpoint behaviors reflected by a flat or curve dewpoint lines on their phase envelops. Overall, the dewpoint pressure is strongly influenced by the temperature.

Several models were mathematically formulated with different sets of the above parameters, expressed in different forms of linear, logarithmic and power relationships. The relationships of these parameters, on the individual and combined basis, to the dewpoint pressure were investigated. Based on the graphical relations, and the r^2 and t-test results, the most important parameters were selected and the least important ones were excluded from the correlation. The following are some of the attempted models:

- $P_d = f(T_R, R_{SP}, P_{SP}, T_{SP}, API)$ (5.1)

- $P_d = f(T_R, R_{SP}, P_{SP}, T_{SP}, \gamma_{gSP}, \gamma_{C7+}, M_{C7+})$ (5.2)

- $P_d = f(T_R, R_{SP}, P_{SP}, T_{SP}, \gamma_{gSP}, \gamma_{C7+}, y_{C1}, y_{C7+})$ (5.3)

- $P_d = f(T_R, R_{SP}, P_{SP}, T_{SP}, \gamma_{gSP}, \gamma_{C7+}, z, B_g)$ (5.4)

The above models contained some of the parameters that were found well correlated with dewpoint pressure, but they were not sufficient to form a model that provides a good accuracy. Then, the concept of pseudocritical properties was introduced in the model to indirectly incorporate the influence of the fluid composition on the dewpoint pressure and improve the prediction accuracy. Since the new model is intended to predict the dewpoint pressures of multi-component gas-condensate systems, the pseudoreduced properties were used relative to reservoir pressure and temperature as discussed in Appendix A. As a result, a strong relationship was found between the dewpoint pressure and the pseudoreduced pressure and temperature of any gas-condensate system.

5.2 Dewpoint Pressure Correlation

The best model that fits the seventy-four (74) experimental dewpoint pressure data was found to be;

$$P_d = e^{\beta_0}\, T_R^{\beta_1}\, R_m^{\beta_2}\, (T_{SP} \cdot P_{SP})^{\beta_3}\, e^{\left(\frac{\beta_4}{T_{pr}} + \frac{\beta_5}{P_{pr}} + \frac{\beta_6}{\gamma_{C7+}}\right)} \tag{5.5}$$

This nonlinear model was linearized by applying logarithmic transformation, which formed the following final linear empirical correlation:

$$\ln(P_d) = \beta_0 + \beta_1 \ln(T_R) + \beta_2 \ln(R_m) + \beta_3 \ln(P_{SP} \cdot T_{SP}) + \frac{\beta_4}{T_{pr}} + \frac{\beta_5}{P_{pr}} + \frac{\beta_6}{\gamma_{C7+}} \tag{5.6}$$

and the mass gas-oil ratio (R_m) is defined as:

$$R_m = \frac{R_{SP} \cdot \gamma_{gSP}}{\gamma_{C7+}} \tag{5.7}$$

where

ln = Natural logarithm (base e)

P_d = Dewpoint pressure (psia)

T_R = Reservoir temperature (°R)

R_{SP} = Separator producing gas-oil ratio (scf/SP bbl)

T_{SP} = Separator temperature (°R)

P_{SP} = Separator pressure (psia)

P_{pr} = Pseudoreduced pressure

T_{pr} = Pseudoreduced temperature

γ_{gSP} = Separator gas specific gravity (relative to air)

γ_{C7+} = Heptanes-plus specific gravity (relative to water)

$\beta_0 = 43.777183$

$\beta_1 = -3.594131$

$\beta_2 = -0.247436$

$\beta_3 = -0.0535257$

$\beta_4 = -4.291404$

$\beta_5 = -3.698703$

$\beta_6 = -4.590091$

5.3 Statistical Analysis of the New Correlation

The statistical analysis of this correlation includes the r^2, the *t*-test statistics, the error distribution analysis, and finally the sensitivity analysis of the independent variables.

5.3.1 Coefficient of Determination

The new model, described by equation 5.6, was developed with a coefficient of determination (r^2) of 0.897, and a correlation coefficient (r) of 0.9471. This indicates that about 95% of the data variation in the dewpoint pressure (dependent variable) can be explained by the model. The new model predicted the dewpoint pressures with an average absolute relative error of 4.33%, compared to the 74 experimental data, and an error standard deviation of 3.93%.

5.3.2 *t*-test Statistics

The significance of the independent variables of the model is indicated in the *t*-test statistics, presented in Table 5.1. The first column shows the variables used in the model. The second column gives the *t*-test statistics for rejecting the null hypothesis that the parameter is equal to zero. The larger the value of the *t*-test corresponding to any variable, the more significant the contribution is of this variable to the model. The Prob. > |t| is the probability of the independent variable of not being significant to be added in the model. All the independent variables have very small values indicating that they all are significant in the model.

Table 5.1: *t*-test for the Model Regression Coefficients (Eq. 5.6)

Independent Variable	*t* for H0: Parameter = 0	Prob > |t|
Intercept	19.695	0.0001
$\ln(T_R)$	-16.790	0.0001
$\frac{1}{T_{pr}}$	-12.229	0.0001
$\ln(R_m)$	-10.218	0.0001
$\frac{1}{P_{pr}}$	-6.952	0.0001
$\ln(P_{SP} \cdot T_{SP})$	-5.396	0.0001
$\frac{1}{\gamma_{C7+}}$	-5.099	0.0001

According to the *t*-test results, listed in Table 5.1, the reservoir temperature with the highest *t*-test value is the most significant parameter in the model. Then, the next influencing parameters with decreasing the degree of significance are the pseudoreduced temperature, the mass gas-oil ratio, the pseudoreduced pressure, the heptanes-plus specific gravity, and the product of the separator pressure and temperature.

5.4 Graphical Error Analysis

5.4.1 Error Distribution Analysis

The error distribution of this new correlation is presented in Figure 5.2 as absolute relative error versus data frequency. It indicates that approximately 65% of the predicted dewpoint pressures fall within 5% average absolute error, and about 95% of the data points are within 10% average absolute error. The error distribution is also presented in a histogram form as shown in Figure 5.3. It shows that the relative error is normally distributed on both sides of the zero error.

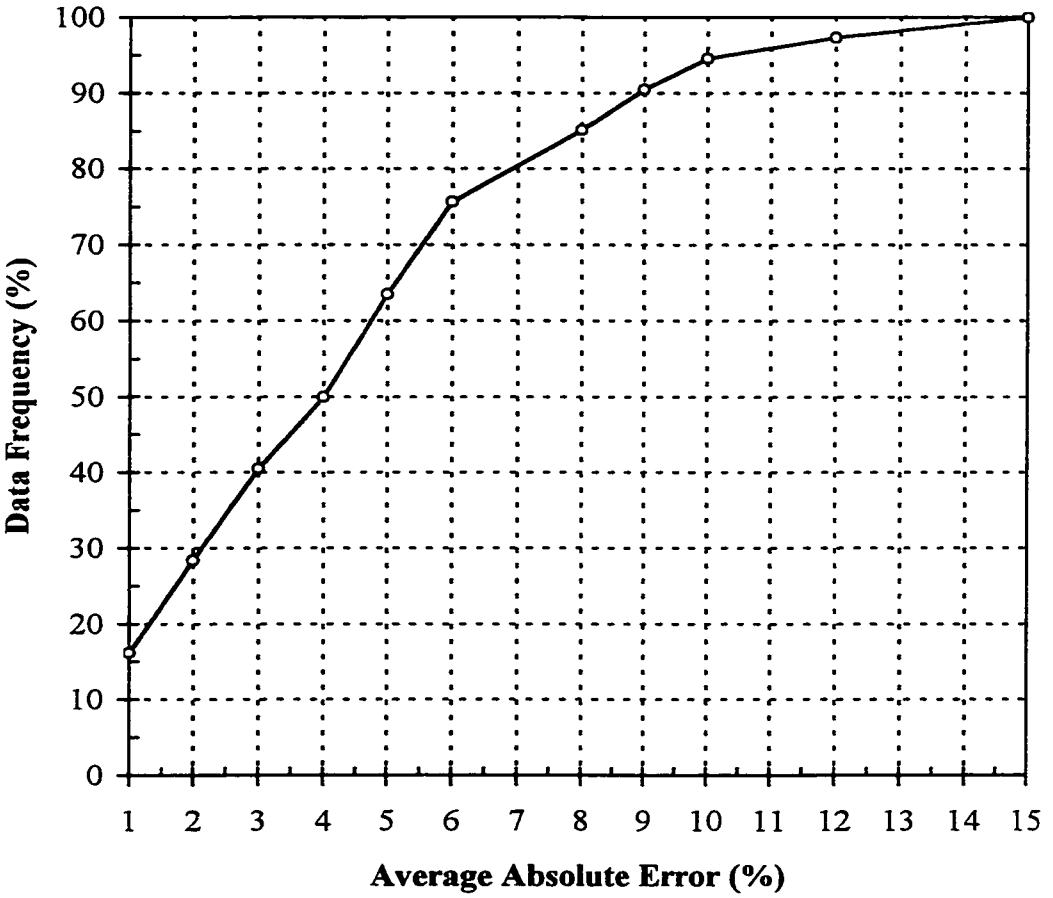

Figure 5.2: New model error distribution (data frequency)

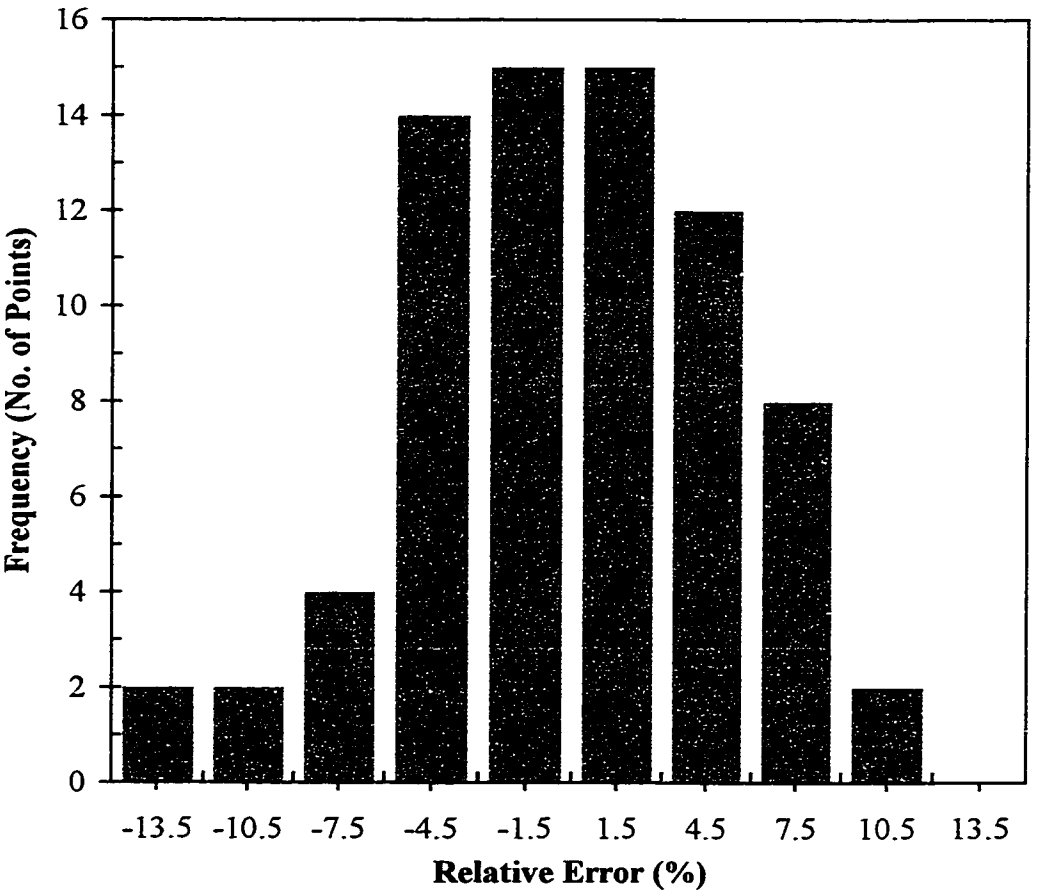

Figure 5.3: New model error distribution histogram

5.4.2 Sensitivity Analysis

The influence of the individual independent variables on the dewpoint pressure was tested. In this sensitivity test, the variation in the dewpoint pressure is observed by varying an independent variable over the practical range while holding the other variables constant at minimum, average and maximum values.

Figure 5.4 shows that dewpoint pressure is very sensitive to the reservoir temperature when other variables are held at minimum values. It is also observed that the sensitivity of the model is reduced as the values of other variables increase. The influence of the reservoir temperature becomes much less significant when other variables are at their maximum values.

Figure 5.5 illustrates that the model is more sensitive to low GOR values than to high GOR values. It is also noticed that the influence of the GOR on the model is decreasing with decreasing the values of other variables.

Figure 5.6 shows that the sensitivity of the model to the pseudoreduced pressure is significant over the full range, but the influence is higher at low values than at high values of pseudoreduced pressure. The effect of

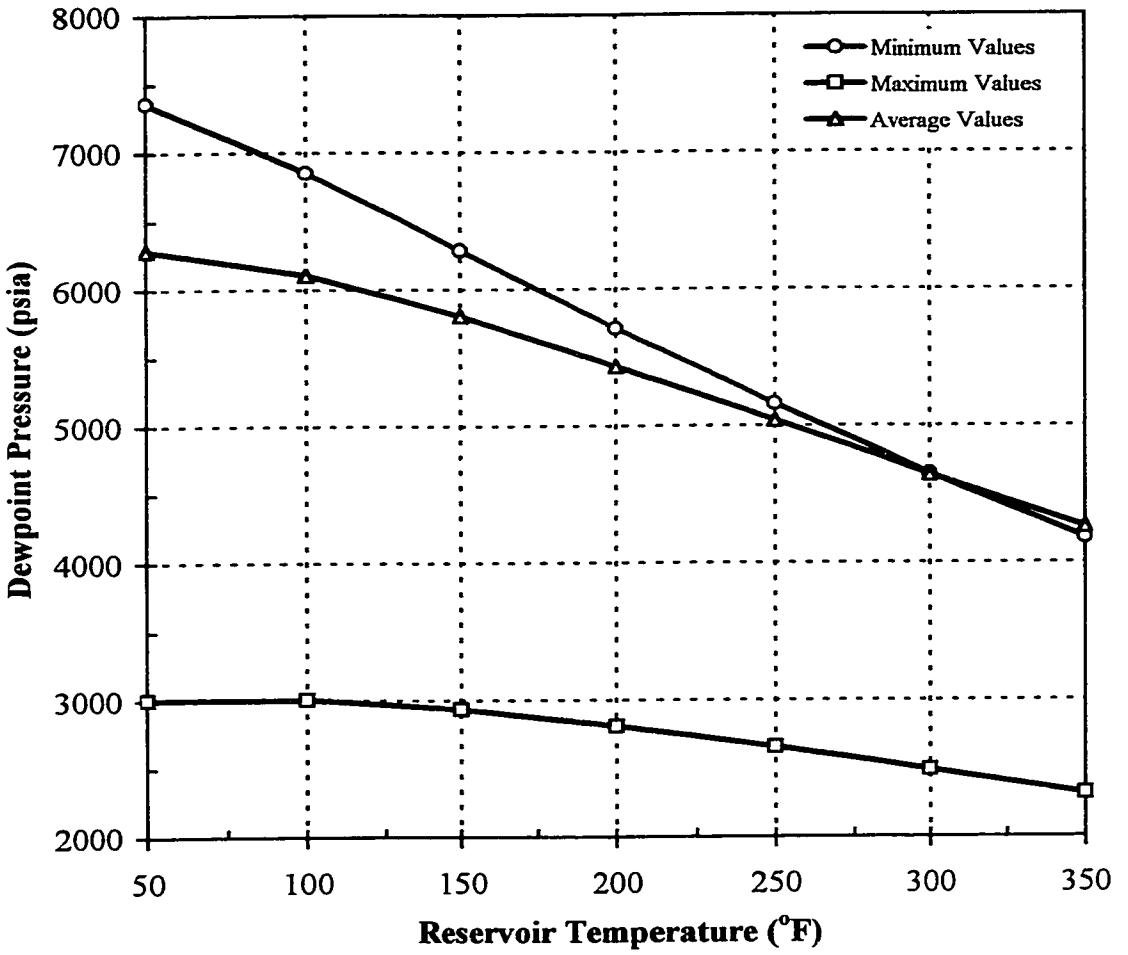

Figure 5.4: Sensitivity of the new model to reservoir temperature

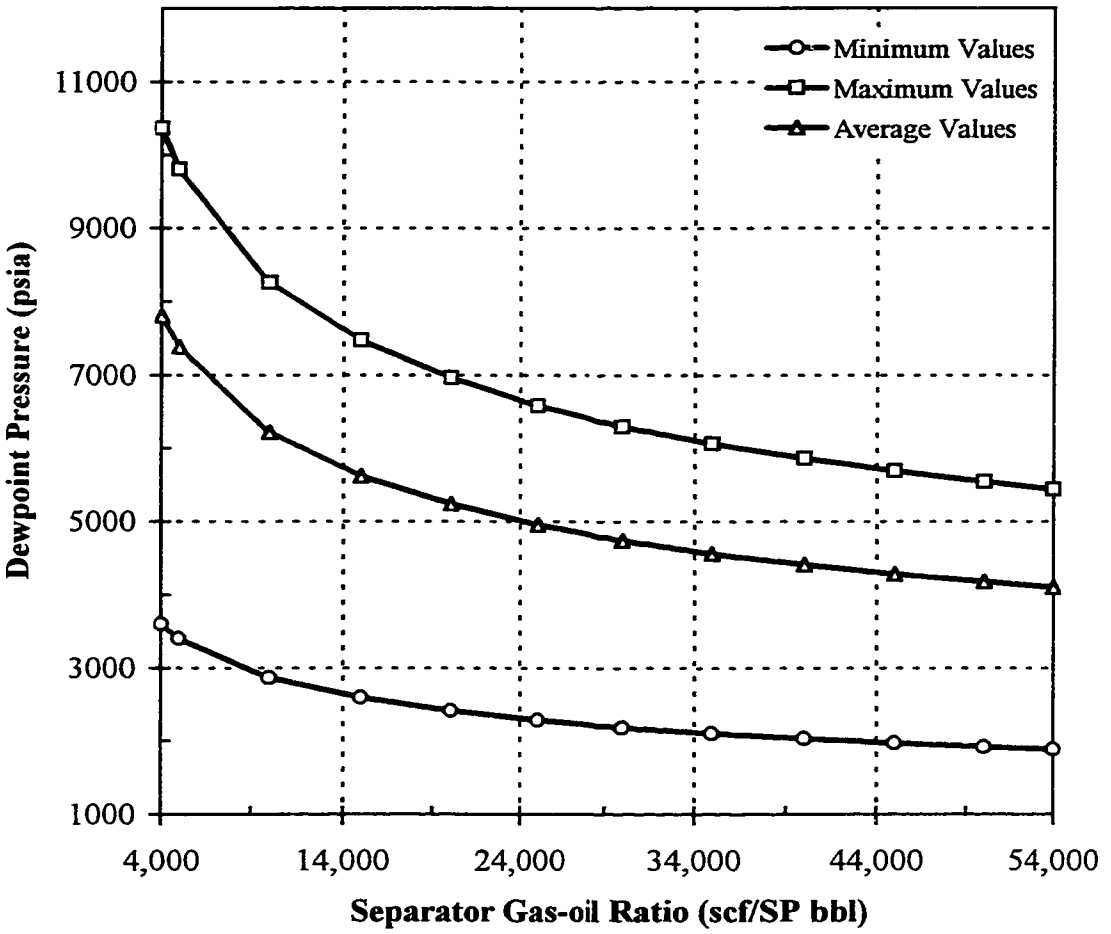

Figure 5.5: Sensitivity of the new model to gas-oil ratio

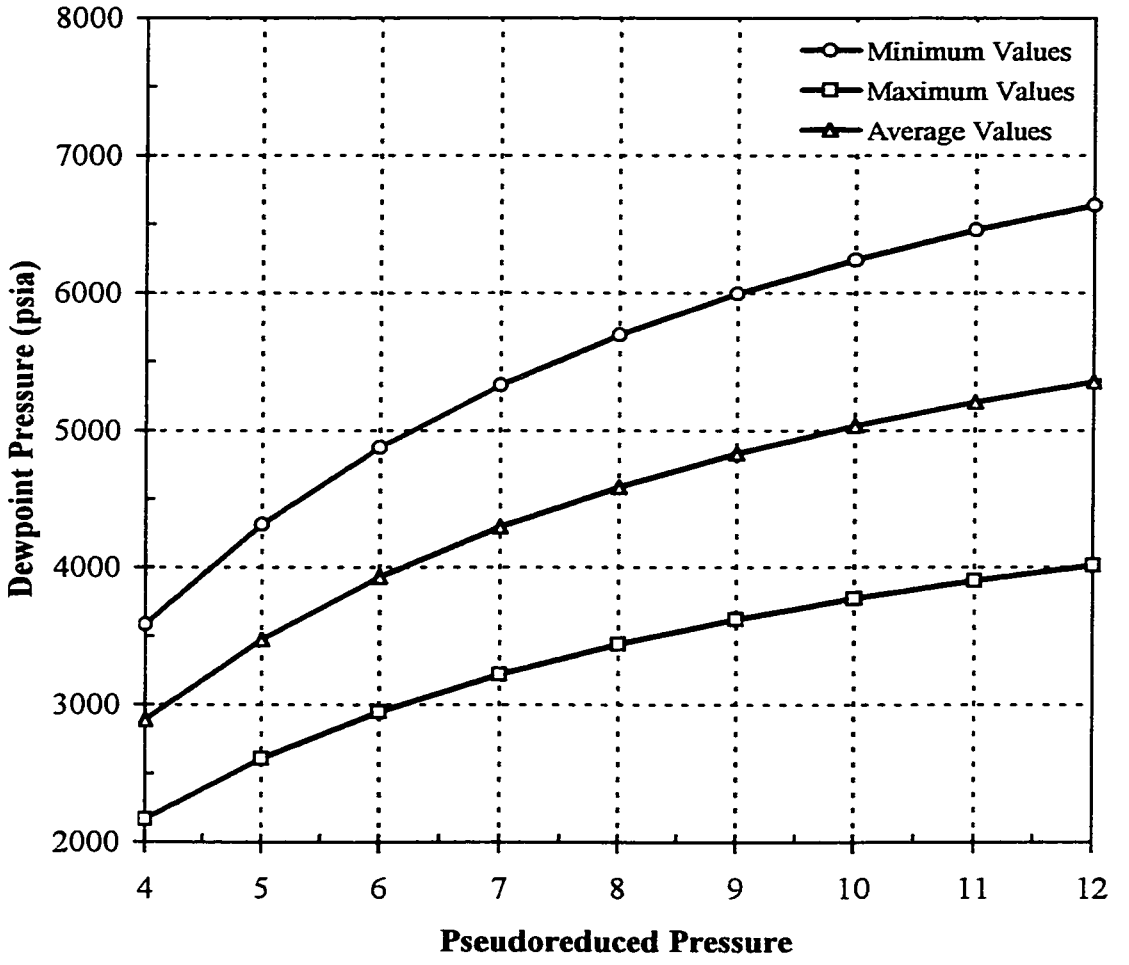

Figure 5.6: Sensitivity of the new model to pseudoreduced pressure

pseudoreduced pressure on the model is reduced as the values of other variables increase.

Figure 5.7 shows that the sensitivity of dewpoint pressure increases with increasing the heptanes-plus specific gravity. It is also observed that the sensitivity to heptanes-plus specific gravity decreases with increasing the values of other variables.

Figure 5.8 illustrates the sensitivity of the model to the combined separator pressure and temperature. The sensitivity is high at very low values of combined pressure and temperature, and it decreases as the values increase. It is also noted that the dewpoint pressure model is more influenced by the combined pressure and temperature when other variables are at their average values.

5.5 New Correlation for Pseudocritical Properties

The pseudocritical pressure and temperature of gas-condensate systems can be estimated using Kay's combination rules presented in equations A.1 and A.2 if the fluid composition is known. If the fluid composition is not available, then some empirical relationships based on the reservoir gas gravity, such as Standing's correlation presented in equations A.11 and A.12, can be used to predict these properties.

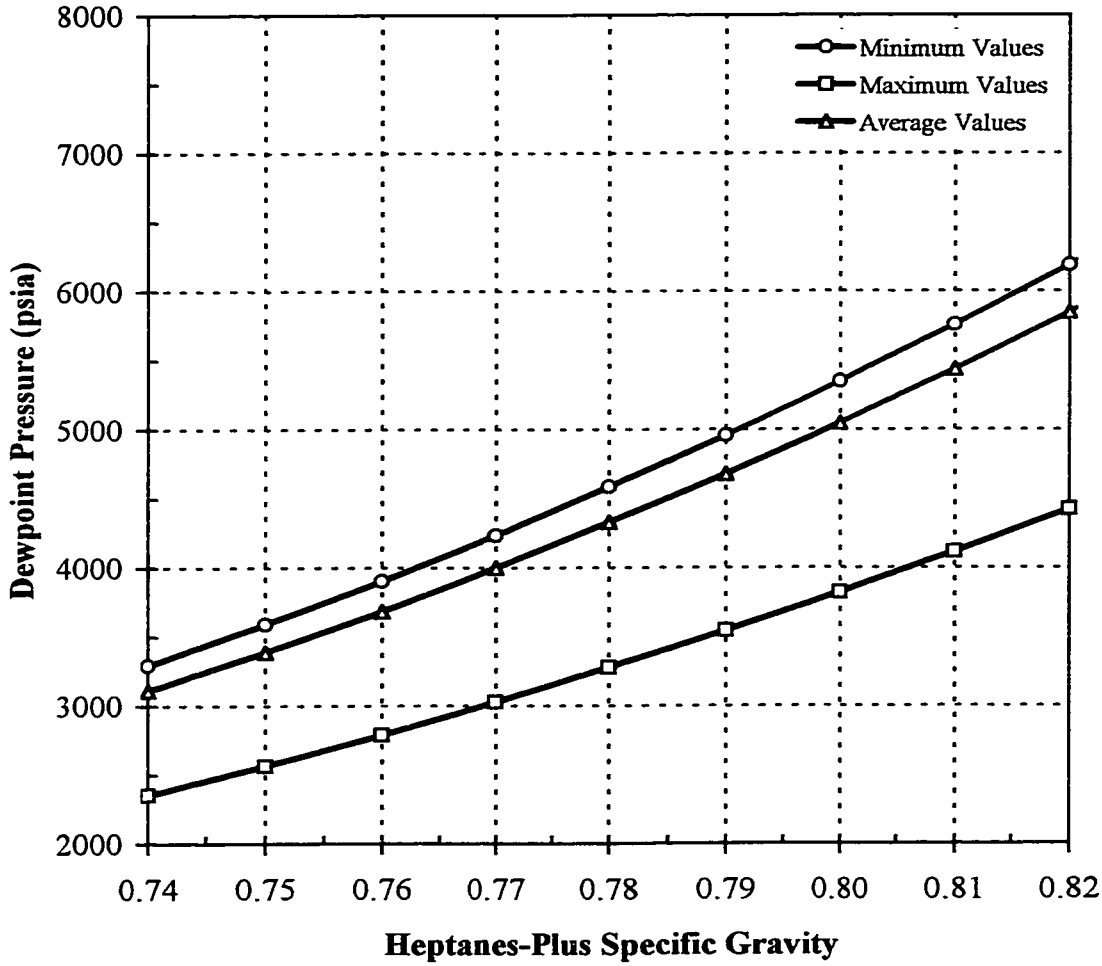

Figure 5.7: Sensitivity of the new model to heptanes-plus gravity

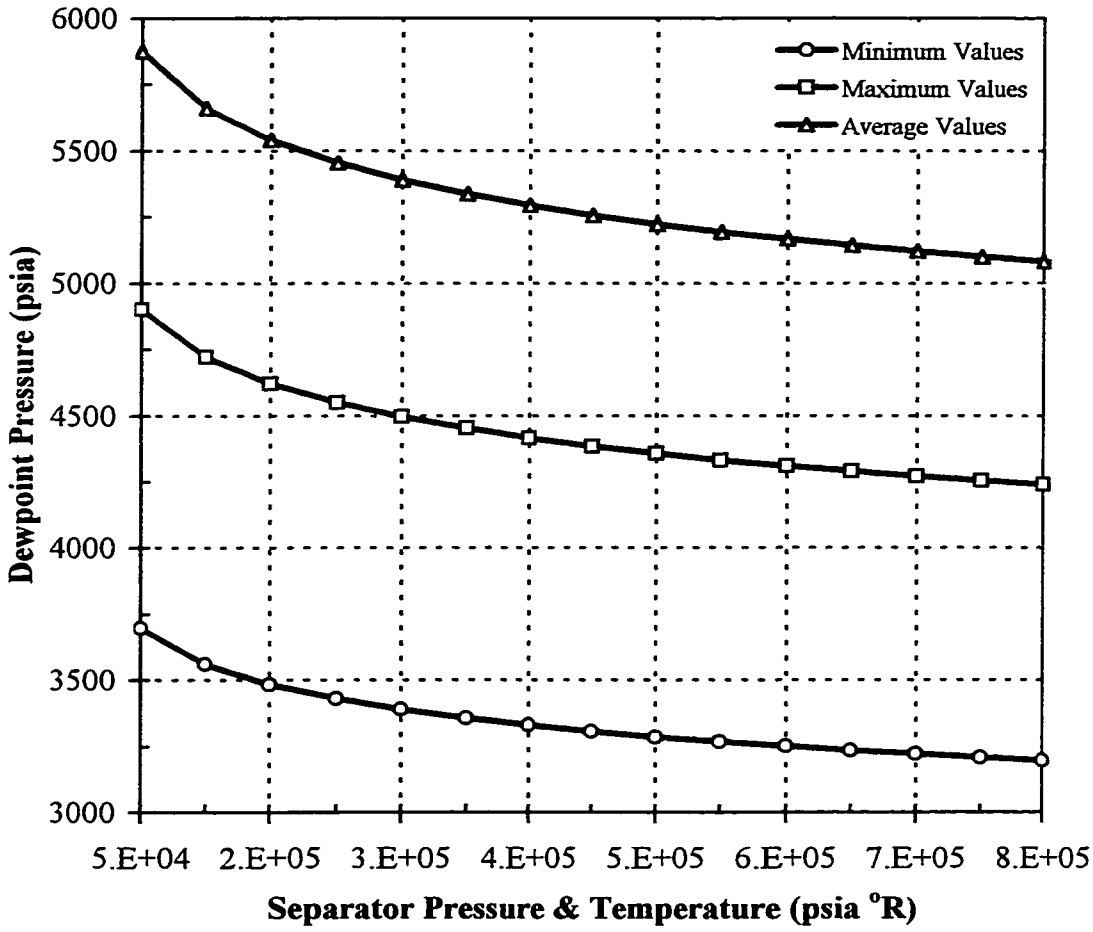

Figure 5.8 : Sensitivity of the new model to separator pressure and temperature

The accuracy of Standing's correlation to predict the pseudocritical properties was evaluated against the Kay's method using the Middle East data sets used in this study. It was found that the average absolute errors in predicting pseudocritical properties are 6% in pseudocritical temperature and 1.2% in pseudocritical pressure. Then, the pseudocritical pressures and temperatures, predicted by Standing's correlation, were used to re-calculate the dewpoint pressures using the new model in equation 5.6. It was found that the average absolute error in predicting dewpoint pressures is 13.5%.

It was attempted to improve the estimation of pseudocritical properties of gas-condensate systems if the fluid composition is unknown. The reservoir gas specific gravities of the 74 Middle East gas-condensate fluids were utilized to develop a new correlation to estimate the pseudocritical properties. The following relationships were found to provide the best fit:

$$P_{pc} = 694.5 - 55.3\gamma_{gR} \tag{5.8}$$

$$T_{pc} = 208.5 + 213.7\gamma_{gR} \tag{5.9}$$

where

P_{pc} = Pseudocritical pressure

T_{pc} = Pseudocritical temperature

γ_{gR} = Reservoir gas specific gravity (relative to air)

With the above correlation, the average absolute errors were found to be 1.8% and 1% in predicting the pseudocritical temperature and pressure respectively. The estimated pseudocritical properties, using equations 5.8 and 5.9, were also used to re-calculate the dewpoint pressures. The new model in equation 5.6 predicted the dewpoint pressures with an average absolute error of 6.4%. Consequently, the new correlation (equations 5.8 and 5.9) provided a better accuracy in the estimation of pseudocritical properties compared to Standing's correlation.

An illustrative calculation example is given in the Appendix C. It illustrates the procedures to be followed for the application of the new correlation. Two solution methods are presented, one is based on the known gas-condensate fluid composition, and the other one is based on the known reservoir gas specific gravity.

CHAPTER 6

CHAPTER 6

EVALUATION OF EXISTING CORRELATIONS

The data sets used to develop the new correlation were utilized to evaluate the prediction accuracy of two existing dewpoint pressure correlations: (1) the Organick and Golding correlation, and (2) the Nemeth and Kennedy correlation. Both statistical and graphical means were used in this comparative evaluation.

6.1 Statistical Error Analysis

Table 6.1 lists five statistical error parameters that are used in this study to evaluate the two existing correlations in comparison with the newly developed correlation. The parameters include the average relative error (E_r), the average absolute relative error (E_a), the minimum relative error (E_{min}), the maximum relative error (E_{max}), and the root mean square relative error (E_{rms}).

Table 6.1: Statistical Accuracy of Dewpoint Pressure Correlations for the Data Used in Model Development

Correlation	E_r	E_a	E_{min}	E_{max}	E_{rms}
Organick and Golding	32.56	32.56	2.12	53.38	35.22
Nemeth and Kennedy	8.57	11.64	0.14	37.4	15.2
This Study	-0.15	4.33	0.01	15.1	5.46

6.1.1 Organick and Golding Correlation

An illustrative example that shows the application of the Organick and Golding graphical correlation to predict the dewpoint pressure of a gas-condensate system is presented in Appendix B.

Table 6.1 shows that using the Organick and Golding correlation to predict the dewpoint pressures of the Middle East gas-condensate systems resulted in an average absolute error of 32.6%, and a maximum relative error of 53.4% compared with the experimental dewpoint pressure data. The root mean square error was 35.22%. These results indicate that the accuracy of this correlation is unsatisfactory.

6.1.1 Nemeth and Kennedy Correlation

The Nemeth and Kennedy correlation was also used to predict the dewpoint pressures of the gas-condensate mixtures. It was found that the E_a is 11.64%, and the E_{max} is 37.4%. The correlation resulted also in the E_{rms} of 15.2%. The Nemeth and Kennedy correlation provided a better accuracy than the Organick and Golding correlation for the gas-condensate systems considered in this study.

6.1.2 The New Correlation

The newly developed correlation predicted the dewpoint pressures with an E_a of 4.33%, a E_{max} of 15.1%, and a E_{rms} of 5.46%. Therefore, the new correlation outperforms the existing correlations.

6.2 Graphical Error Analysis

Graphical means help in visualizing the accuracy of a correlation. Two graphical analysis techniques were considered in this study for comparative evaluation of the existing correlations with the new correlation. These techniques included the crossplot and parameter grouping analysis.

6.2.1 Crossplot

The crossplots of estimated versus experimental values of the dewpoint pressures are shown in Figures 6.1 through 6.3. For the purpose of accuracy analysis, both zero-error line or the 45° line and the $\pm$ 10% error variance are drawn on these plots.

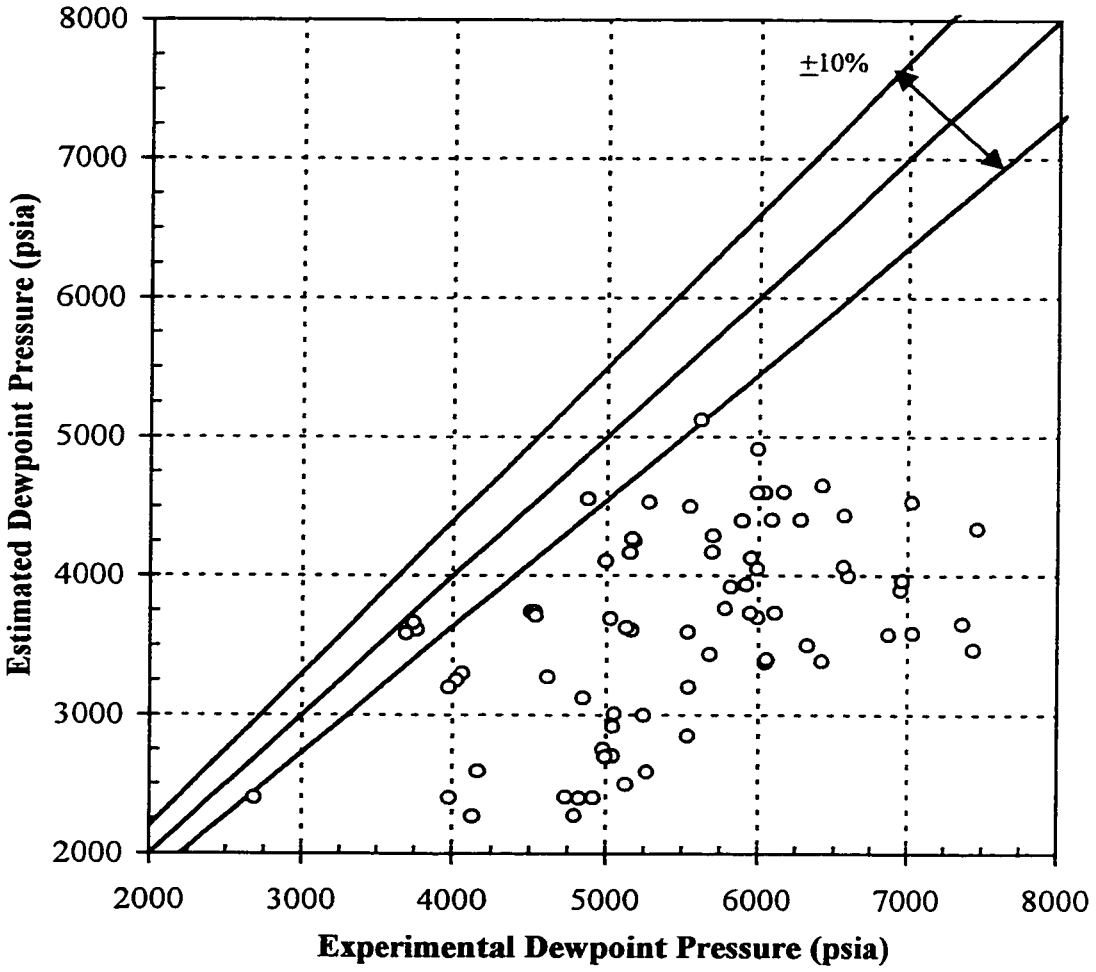

Figure 6.1: Crossplot of dewpoint pressure correlation (Organick and Golding)

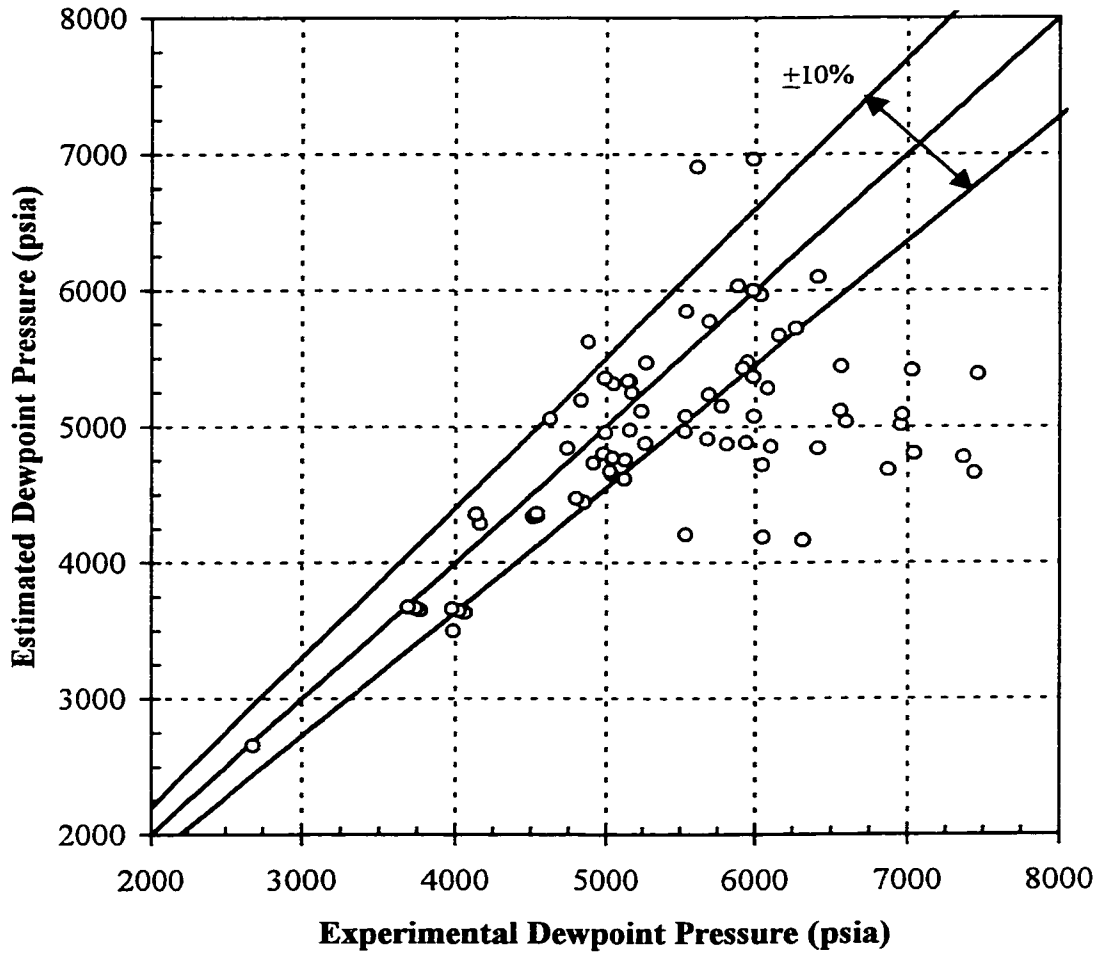

Figure 6.2: Crossplot of dewpoint pressure correlation (Nemeth and Kennedy)

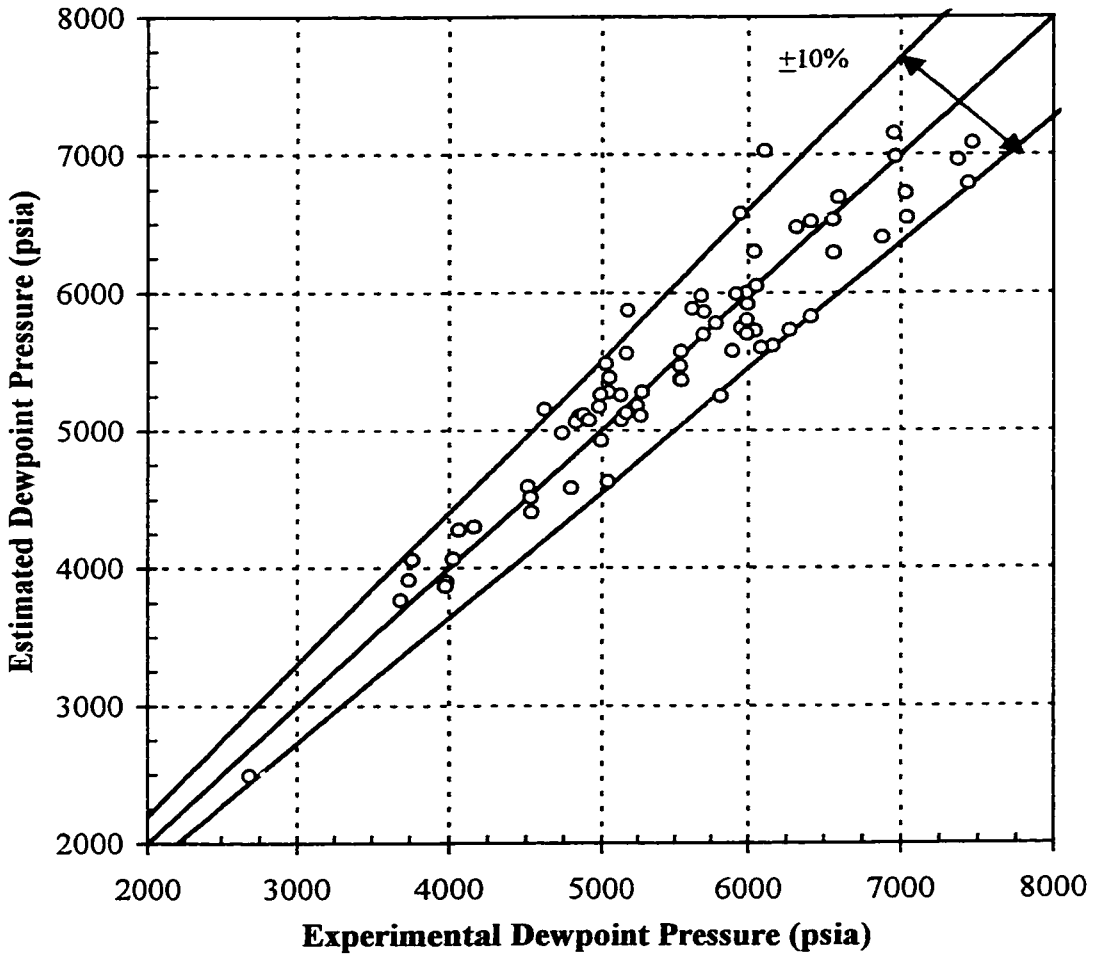

Figure 6.3: Crossplot of dewpoint pressure correlation (This Study)

The crossplot of Organick and Golding, presented in Figure 6.1, shows that the majority of data points are widely scattered and highly deviated from the 45° line. The crossplot also reveals that this correlation always underestimates the dewpoint pressures compared to the experimental values.

The crossplot of Nemeth and Kennedy correlation, presented in Figure 6.2, shows that the correlation dewpoint pressure predictions were within $\pm$ 10% error variance for dewpoint pressures less than 5500 psia. However, the correlation had the tendency to underestimate the dewpoint pressures at pressures higher than 5500 psia with increasing the deviation as the dewpoint pressure increases.

The crossplot of the newly developed correlation, presented in Figure 6.3, shows clearly that the majority of the data points fall within $\pm$10% variance. It is also observed from this crossplot that the data points are well scattered closely around the 45° line. Overall, The newly developed correlation showed a better prediction accuracy and a more consistent error scatter in the data points than the other two existing correlations.

6.2.2 Parameter Grouping Analysis

The degree of error randomness or error distribution with the change in any parameter was tested by plotting the average absolute error versus the groups or ranges of any variable.

Figure 6.4, is a plot of average absolute error versus ranges of dewpoint pressure. This plot shows that both existing correlations are influenced by the range of the dewpoint pressure, and it is noted that the average absolute error increases as the dewpoint pressure increases. However, the new correlation is showing almost constant average absolute error over different ranges of dewpoint pressure.

The change in the average absolute error over the ranges of reservoir temperature is shown in Figure 6.5. The Organick and Golding correlation showed random errors with the change in reservoir temperature. On the other hand, the Nemeth and Kennedy correlation is strongly influenced by the ranges of reservoir temperature with decreasing the E_a as the reservoir temperature increases. The correlation showed a constant E_a at temperatures greater than 250°F. The plot shows also that the error in the new correlation is not influenced by the change in reservoir temperature. This is indicated by random errors over different ranges of temperature. The least error occurred at temperature range of 200-250°F.

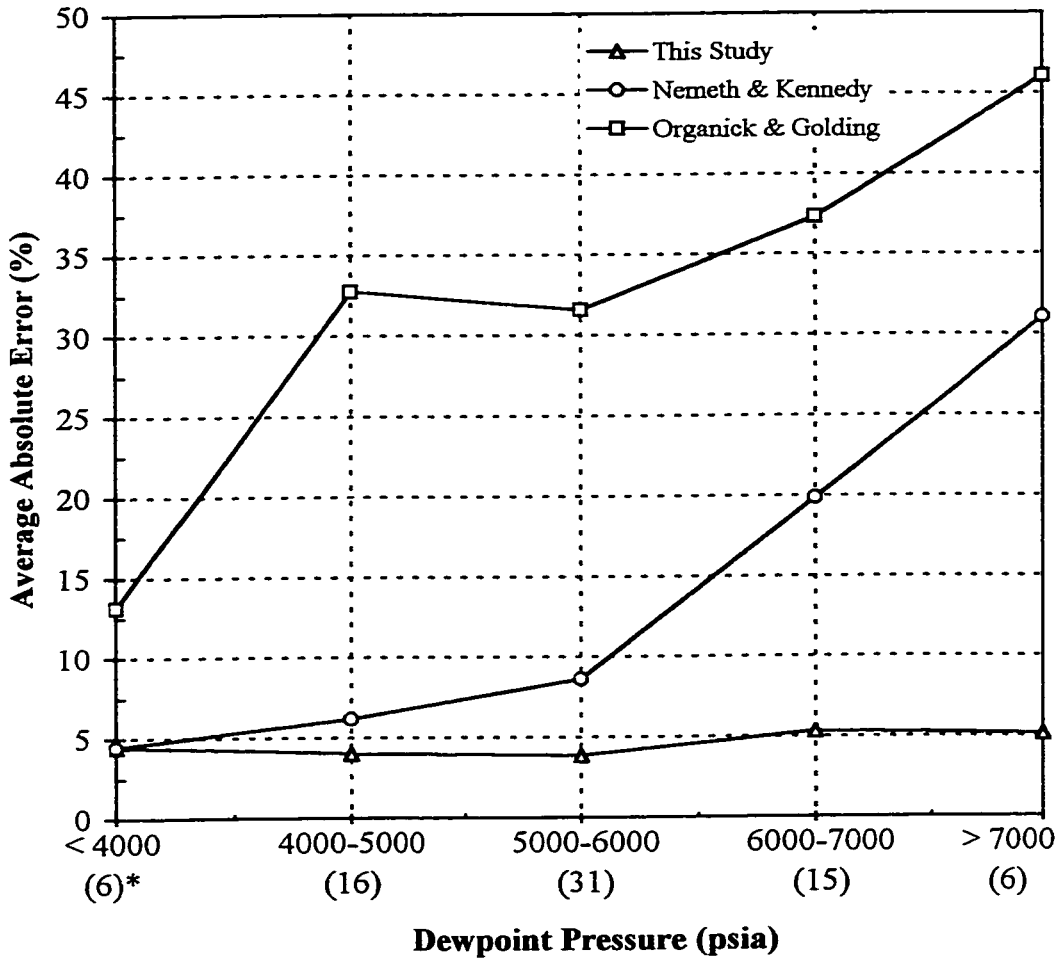

Figure 6.4: Accuracy of correlations for ranges of dewpoint pressure (* number of data points)

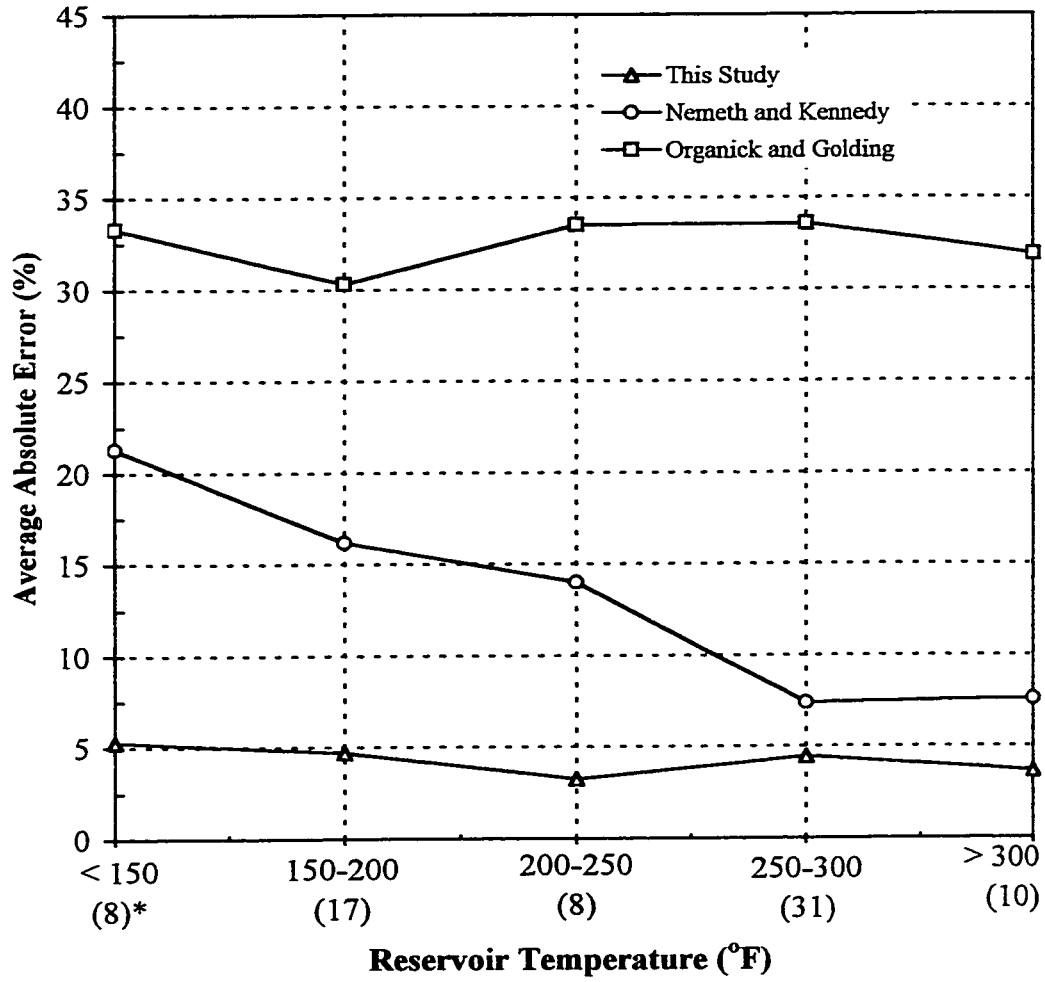

Figure 6.5: Accuracy of correlations for ranges of reservoir temperature (* number of data points)

Figure 6.6 is a plot of the E_a versus the ranges of separator gas-oil ratio. It illustrates that the E_a of both existing correlations increased with increasing the separator GOR at values less than 30,000 scf/SP bbl. At higher GOR values, the E_a started to decrease. However, the error in the new correlation is not affected by the separator GOR. The new correlation showed almost constant E_a over the full range of separator GOR.

In Figure 6.7, a plot of the E_a versus the concentration of acid gas (H_2S + CO_2), it is obvious that both existing correlations are influenced by the change in acid gas concentrations since they are directly relating the dewpoint pressure to the fluid composition. Both correlations showed an increase in the E_a with increasing the acid gas concentration, and the Organick and Golding correlation is more sensitive to the change in acid gas concentration than the Nemeth and Kennedy correlation. In contrast, the new correlation was showing a constant E_a over all ranges of acid gas concentration, which proves that the accuracy of the new correlation is not affected by the presence of acid gases in the ranges encountered in this study.

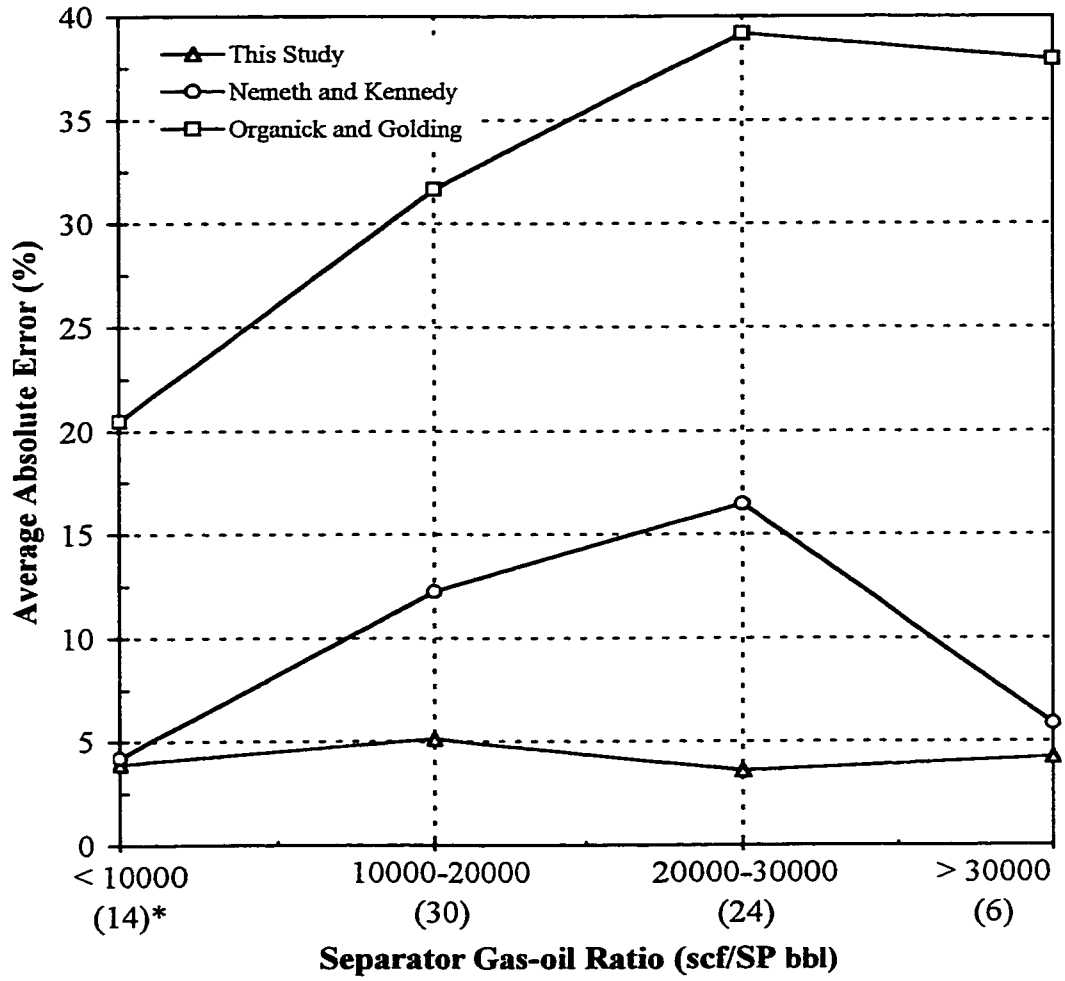

Figure 6.6: Accuracy of correlations for ranges of separatror gas-oil ratio (* number of data points)

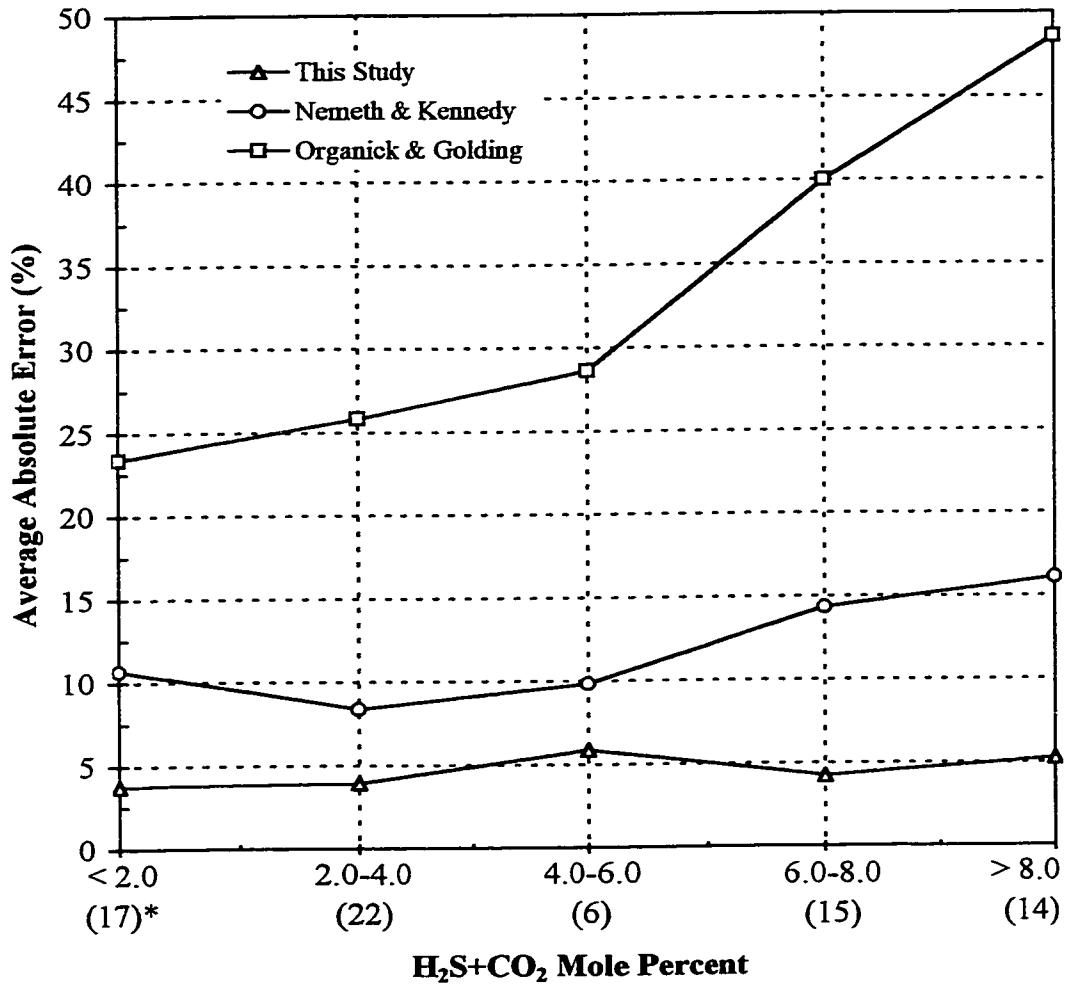

Figure 6.7: Accuracy of correlations for ranges of acid gas concentrations (* number of data points)

CHAPTER 7

CHAPTER 7

VALIDATION OF THE NEW CORRELATION

In order to examine the applicability and reliability of the newly developed empirical dewpoint pressure correlation, it was validated using twenty (20) data sets that were not used in the development of the new correlation. These collected data sets include different properties and conditions of gas-condensate systems prevailing in the Middle East region. The new correlation was also compared against the existing correlations to evaluate its accuracy.

Table 7.1 summarizes the results of error analysis of the three correlations. The table shows that the Organick and Golding correlation has very high average absolute and maximum errors. The Nemeth and Kennedy correlation shows a better accuracy than the Organick and Golding correlation. The errors in the existing correlations using the new data sets

Table 7.1: Statistical Accuracy of Dewpoint Pressure Correlations for the Data Used in Model Validation

Correlation	E_r	E_a	E_{min}	E_{max}	E_{rms}
Organick and Golding	35.43	35.43	7.44	44.83	36.74
Nemeth and Kennedy	11.29	11.29	1.78	20.83	12.70
This Study [1]	-0.16	3.72	0.24	9.41	4.38
This Study [2]	2.60	3.35	0.17	9.05	4.14

Notes: (1) The pseudocritical properties were estimated based on the gas-condensate fluid composition using Kay's method.
(2) The pseudocritical properties were estimated based on the reservoir gas specific gravity using equations

are considered very close to the errors resulted from the data sets used to develop the new correlation.

Since the new correlation was derived based on data sets represented gas-condensate systems in the Middle East, its best performance is expected for the gas-condensate systems of similar properties and conditions. The accuracy of the new correlation was tested using two different methods for estimation of pseudocritical pressure and temperature, based on the available fluid composition and the gas specific gravity correlation for unknown fluid composition. The predictions of the new correlation for the dewpoint pressure were found within less than 4% average absolute error, and with a maximum relative error of less than 10% using both pseudocritical-property estimation methods.

CHAPTER 8

CHAPTER 8

CONCLUSIONS

As a result of this study, which employed the multiple linear regression analyses to develop a new empirical dewpoint pressure correlation using field production and experimental data for the Middle East gas-condensate systems, the following conclusions can be drawn:

1. A new empirical correlation to predict the gas-condensate dewpoint pressure with a good accuracy has been developed.

2. The developmental approach of this new correlation is based on some readily available gas-condensate properties and parameters. Most of these parameters were not considered in the existing correlations.

3. Comparative evaluation of existing correlations was made using statistical and graphical error analyses. It showed that the new correlation outperforms the existing correlations.

4. The empirical correlation developed in this study was validated using sets of data, which were not used in the development of this correlation, and the model provided better accuracy than the existing correlations.

5. The new correlation is considered more relevant and applicable to the Middle East gas-condensate properties and conditions than the existing correlations since the new model has been developed based on a large number of data sets for the Middle East gas-condensate fluid samples.

6. New correlations to estimate pseudocritical properties as function of gas relative density were developed based on Middle East gas-condensate data. Higher accuracy was obtained when these correlations are used instead of Standing's ones.

APPENDICES

Appendix A

Background on Properties of Gas-Condensate Systems

A.1 Characteristics and Behavior:

The phase diagram of a retrograde gas, shown in Figure A.1, has a critical temperature less than reservoir temperature and a cricondentherm greater than reservoir temperature. Initially, the retrograde gas is totally gas in the reservoir, point 1. As the reservoir pressure decreases, the retrograde gas exhibits a dew point, point 2. As the pressure is more reduced, liquid starts to condense from the gas to form a free liquid in the reservoir. This liquid will normally not flow and cannot be produced. [2]

The reservoir pressure path on the phase diagram, Figure A.1, indicates that at some low pressure the liquid begins to re-vaporize. This occurs in the laboratory; however, it probably does not occur to a much extent in the reservoir because during production the overall composition of the reservoir fluid changes. [2]

The lower limit of the initial producing GOR for a retrograde gas is approximately 3300 scf/STB. The upper limit is not well defined; but

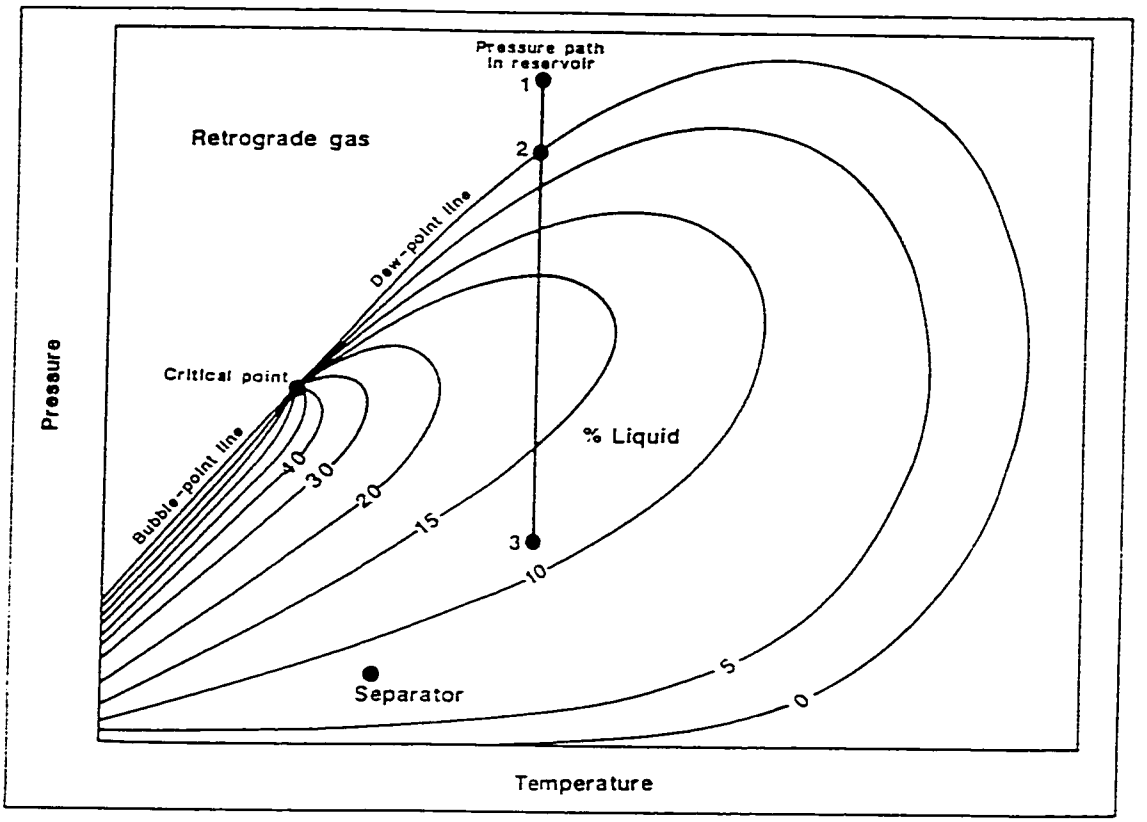

Figure A.1: Phase diagram of a typical retrograde gas with line of isothermal reduction of reservoir pressure, 123, and surface separator conditions. [2]

values of over 150,000 scf/STB have been observed. These high GOR's indicate that the phase diagram is much smaller than the one shown in Figure A.1. Gases with high GOR's have cricondentherms close to reservoir temperature and drop very little retrograde liquid in the reservoir. An initial producing GOR of 3,000 to 5,000 scf/STB indicates a very rich retrograde gas, one which will condense sufficient liquid to fill 35% or more of the reservoir volume. Stock-tank liquid gravities of gas-condensate fluids are between 40 and 60 API and increase as reservoir pressure falls below the dewpoint pressure. The liquid can be lightly colored, brown, orange, greenish, or water-white. However, Color alone is not a good indicator of whether a particular hydrocarbon liquid is condensate or oil. [1,2,12]

It is not normally expected to see a retrograde behavior at reservoir pressures below 2,500 psi. At these relatively low pressures, the condensate is usually very light in color and high in gravity. The lower gravities and the darker colors observed in condensates are indicators of heavy hydrocarbons. High pressure is required to vaporize heavy hydrocarbons; consequently, a reservoir producing a dark condensate should be expected to have a high dewpoint pressure. The heptanes-plus fraction of gas-condensates is usually less than 12.5 mole percent. There is a fairly sharp dividing line between oils and condensates from a compositional standpoint. Reservoir fluids that contain heptanes and heavier in

concentrations of more than 12.5% are almost always in the liquid phase in the reservoir. Those with less than 12.5% are almost always in the gas phase in the reservoir. [12]

A.2 Pseudocritical Properties

The pseudocritical pressure and temperature for gas-condensate mixtures are used in place of true critical pressure and temperature of hydrocarbon mixtures. The pseudocritical values have no physical significance, but merely provide a means of correlating mixture properties applicable to corresponding states principle, which has been extended to cover mixtures of gases closely related. The gas pseudocritical properties are usually used to estimate the gas compressibility factors, needed in material-balance equations to estimate initial gas in place and reserves.[8]

The pseudocritical properties of gas-condensate mixtures can be estimated using either the simple Kay's method, or the more rigorous Sutton's method if the well-stream gas composition is known. [2] In the case of unknown well-stream gas composition, the pseudocritical properties can be estimated using correlations based on well-stream gas gravity, such as Standing's correlation. [8]

Kay proposed that the pseudocritical pressure and temperature be calculated using weighted average relationships (Kay's mixing rules) for known gas composition; [2,8,11]

$$P_{pc} = \sum_{i=1}^{n} y_i \cdot P_{ci} \qquad (A.1)$$

$$T_{pc} = \sum_{i=1}^{n} y_i \cdot T_{ci} \qquad (A.2)$$

where

P_{pc} = pseudocritical pressure, psia

T_{pc} = pseudocritical temperature, °R

P_{ci} = critical pressure of component i

T_{ci} = critical temperature of component i

y_i = mole fraction of component i in the gas mixture

The reduced states for gas mixtures are called the pseudoreduced pressure and temperature. The physical properties of gas mixtures are correlated with these pseudoreduced properties in the same manner that properties of pure gases are correlated with reduced temperature and reduced pressure. They are expressed relative to pseudocritical pressure and temperature; [8,11]

$$P_{pr} = \frac{P}{P_{pc}} \tag{A.3}$$

$$T_{pr} = \frac{T}{T_{pc}} \tag{A.4}$$

where

P_{pr} = pseudoreduced pressure of the gas mixture

T_{pr} = pseudoreduced temperature of the gas mixture

Natural gases often contain nitrogen, carbon dioxide and/or hydrogen sulfide, which can affect the calculations of pseudocritical properties. Wichert and Aziz have examined the effect of carbon dioxide and hydrogen sulfide on the calculation and have proposed calculation procedures for adjusting pseudocritical properties. The pseudocritical adjusting parameter (ε), which is a function of the concentrations of CO_2 and H_2S in the sour gas, is then used according to the following mathematical expression; [10]

$$\varepsilon = 120(A^{0.9} - A^{1.6}) + 15(B^{0.5} - B^{4.0}) \tag{A.5}$$

and the corrected pseudocritical pressure and temperature are as follows;

$$P_{pc}' = \frac{P_{pc} T_{pc}'}{T_{pc} + B(1-B)\varepsilon} \tag{A.6}$$

$$T_{pc}' = T_{pc} - \varepsilon \tag{A.7}$$

where

P_{pc}' = pseudocritical pressure, psia, adjusted for nonhydrocarbon

T_{pc}' = pseudocritical temperature, °R, adjusted for nonhydrocarbon

A = sum of the mole fractions of H_2S and CO_2 in the gas mixture

B = mole fraction of H_2S in the gas mixture

In addition, quantities of high molecular weight hydrocarbons, which are usually lumped together and reported as heptanes plus, are in most cases present in the gas and can significantly affect the accuracy of calculated pseudocritical properties. Sutton and Whitson evaluated several methods for estimating the pseudocritical properties of the heptanes-plus fraction. They recommended the Lee-Kessler equations to be used for these calculations. [11]

$$P_{pc} = EXP\left[8.3634 - \frac{0.0566}{\gamma_{C7+}} - (0.24244 + \frac{2.2898}{\gamma_{C7+}} + \frac{0.11857}{\gamma_{C7+}^{2}})10^{-3}T_B + (1.4685 + \frac{3.648}{\gamma_{C7+}} + \frac{0.47227}{\gamma_{C7+}^{2}})10^{-7}T_B^{2} - (0.42019 + \frac{1.6977}{\gamma_{C7+}^{2}})10^{-10}T_B^{3}\right] \quad (A.8)$$

$$T_{pc} = 341.7 + 811\gamma_{C7+} + (0.4244 + 0.1174\gamma_{C7+})T_B + \frac{(0.4669 - 3.2623\gamma_{C7+})10^{5}}{T_B} \quad (A.9)$$

Whitson has provided an equation suitable for estimating the boiling point of the heptanes plus from its specific gravity and molecular weight if the experimental boiling point is not available; [17]

$$T_B = (4.5579M_{C7+}^{0.15178}\gamma_{C7+}^{0.15427})^{3} \quad (A.10)$$

where

T_B = the heptanes plus boiling point, °R

γ_{C7+} = the specific gravity of heptanes plus fraction

M_{C7+} = apparent molecular weight of heptanes plus fraction

In cases where the composition of the gas-condensate system is not available, the pseudocritical properties can be predicted from the specific gravity of the reservoir gas (γ_{gR}) using Standing's correlation; [8,11]

$$P_{pc} = 706 - 51.7\gamma_{gR} - 11.1\gamma_{gR}^{2} \quad \text{(A.11)}$$

$$T_{pc} = 187 + 330\gamma_{gR} - 71.5\gamma_{gR}^{2} \quad \text{(A.12)}$$

A.3 Gas Specific Gravity

The specific gravity is the ratio of the density of a gas at a given temperature and pressure to the density of air at the same temperature and pressure, usually near standard conditions. The gas specific gravity is independent of temperature and pressure, where the gas obeys the ideal gas law. As discussed above, the reservoir-gas specific gravity can be used to estimate gas pseudocritical properties.

The laboratory measurement of reservoir gas specific gravity provides the most accurate determination. The reservoir gas specific gravity can also be estimated from the known reservoir gas composition. The apparent molecular weight is defined mathematically by the following equation:

$$M_a = \sum_{i=1}^{n} y_i \cdot M_i \qquad (A.13)$$

where

M_a = apparent molecular weight of the gas mixture

y_i = mole fraction of ith component in the mixture

M_i = molecular weight of the ith component in the mixture

Then, assuming the behavior of both the gas mixture and the air is described by the ideal gas equation, the reservoir-gas specific gravity can be expressed by the following relationship:

$$\gamma_{gR} = \frac{M_a}{M_{air}} = \frac{M_a}{28.96} \qquad (A.14)$$

If compositional analysis is unavailable, then the field production information in the form of a mathematical recombination expression can be used to estimate the specific gravity of the reservoir gas with a reliable accuracy. If the properties and quantities of all surface gas streams are known, then the surface gas can be represented by a weighted average of specific gravities of the separator gas and stock-tank gas. Then, the reservoir-gas specific gravity is calculated as;

$$\gamma_{gR} = \frac{R\gamma_{gs} + 4584\gamma_o}{R + 132{,}800\frac{\gamma_o}{M_o}} \tag{A.15}$$

where

$R =$ surface producing gas-oil ratio, scf/STB

$\gamma_o =$ specific gravity of tank oil (water = 1.0)

$M_o =$ molecular weight of the tank oil (condensate)

$\gamma_{gs} =$ average specific gravity of surface separators gas (air = 1)

In many cases, only the primary separator gas-production rate, the gas specific gravity, and the stock-tank liquid production rate and its gravity are known. In this case, the empirical correlation developed by McCain can be used to estimate the reservoir gas specific gravity within 2% of laboratory- determined values provided that non-hydrocarbon gas content is not high. [15,16]

$$\gamma_{gR} = \frac{R_{SP}\gamma_{gSP} + 4{,}600\gamma_o + G_{pa}}{R_{SP} + V_{eq}} \tag{A.16}$$

where

V_{eq} = vapor equivalent of primary separator liquid (scf/STB)

G_{pa} = additional gas production (scf/STB) times specific gravity

R_{SP} = producing gas-oil ratio from primary separator (scf/STB)

P_{SP} = primary separator pressure (psig)

T_{SP} = primary separator temperature (°R)

γ_o = stock-tank oil specific gravity

γ_{gSP} = specific gravity of gas from primary separator

Two empirically derived correlations were developed to estimate the variables V_{eq} and G_{pa} at any given conditions, See reference 16 for the details of these correlations and its regression coefficients.

Appendix B

Organick and Golding Correlation [5]

The correlation is given in the form of a set of 14 working charts (Figures B.1 through B.14)[5] in which saturation pressures, either retrograde dewpoints or bubble points, are plotted versus temperature forming partial phase envelops for the gas mixtures. On each chart, the saturation pressure is related directly to the composition of the mixture with the aid of two generalized composition characteristics; (1) the molal average boiling point ($\overline{B}$) in °R, and (2) the modified average equivalent molecular weight (W_m), where,

$$\overline{B} = \sum \text{ (mol fraction)}_i.\text{(boiling point)}_i$$

$$W_m = \sum \text{ (weight fraction)}_i.\text{(equivalent molecular weight)}_i$$

In order to clarify the procedures to be followed when applying this correlation, the following illustrative example is given here.

Illustrative Problem: [5]

Predict the dewpoint pressure at 199°F for a well effluent having the chemical composition and the C_{7+} properties given in Table B.1:

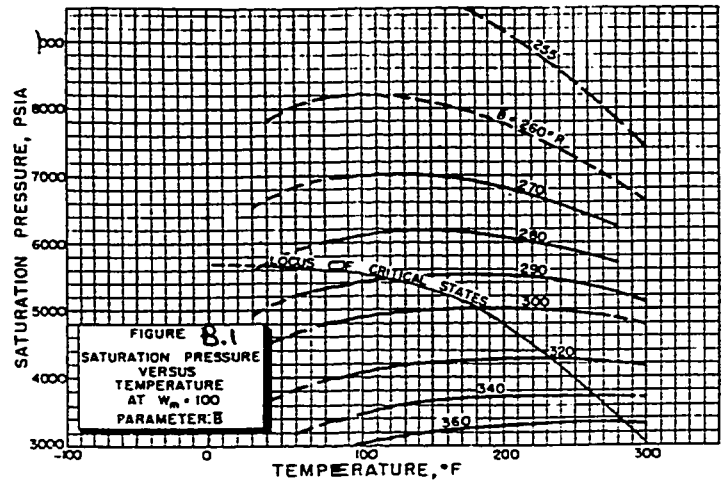

FIG. B.1

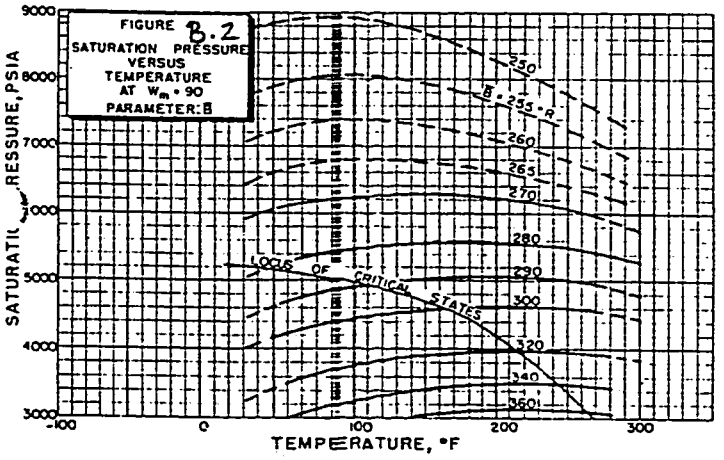

FIG. B.2

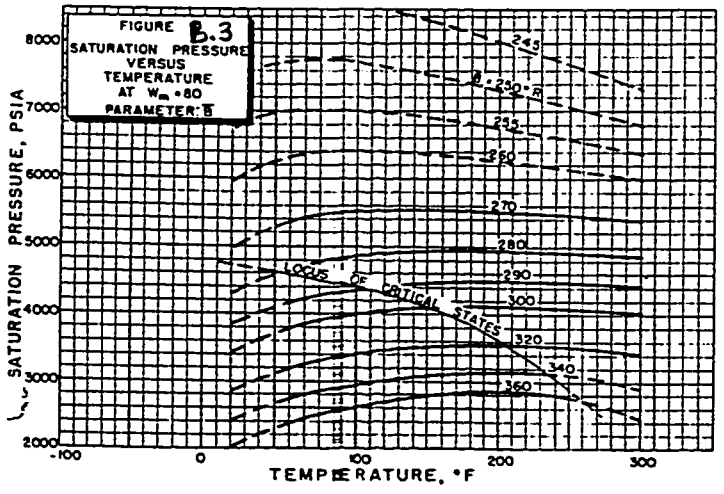

FIG. B.3

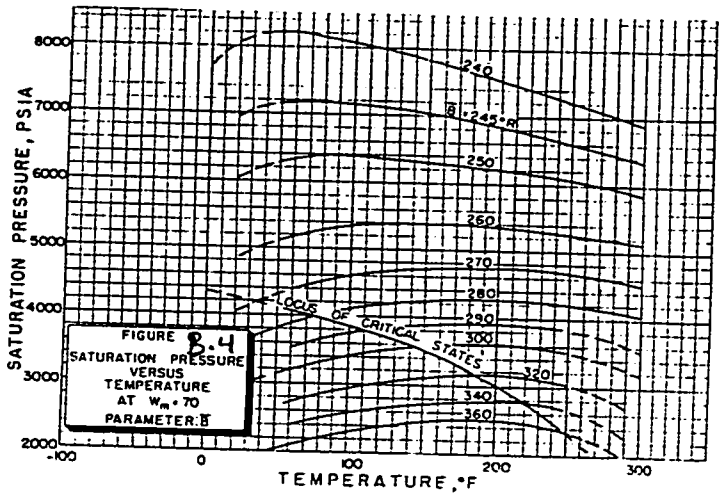

FIG. B.4

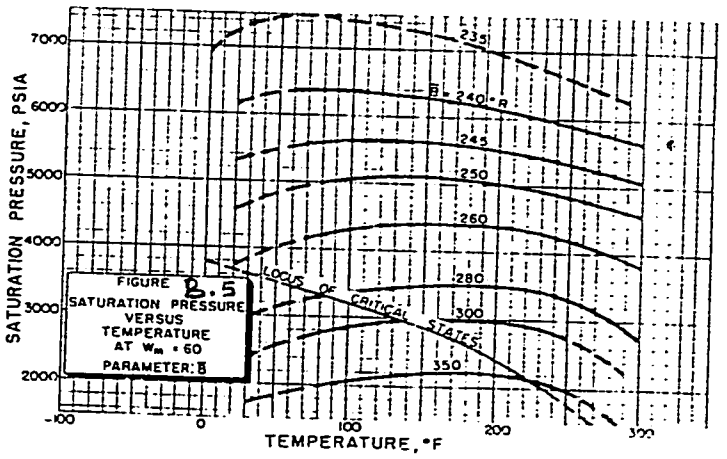

FIG. B.5

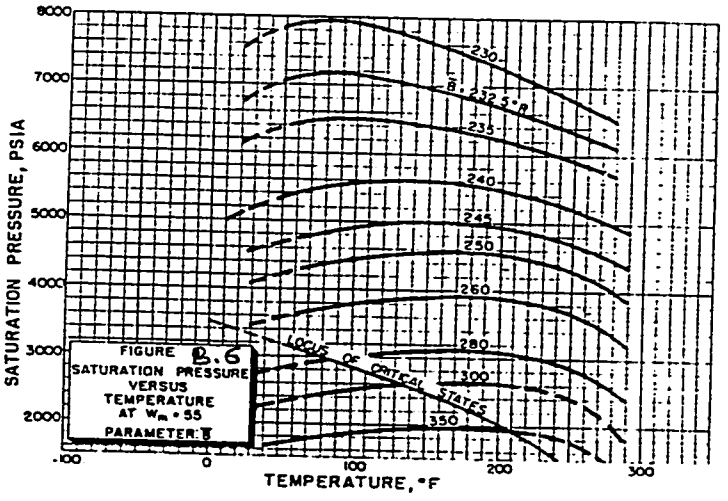

FIG. B.6

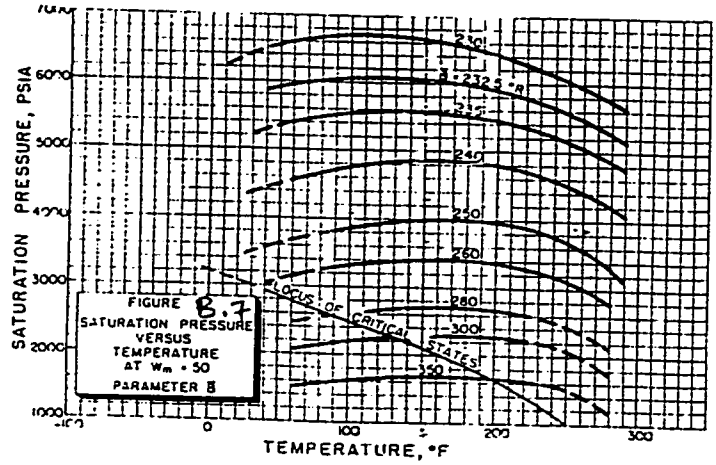

FIG. B.7

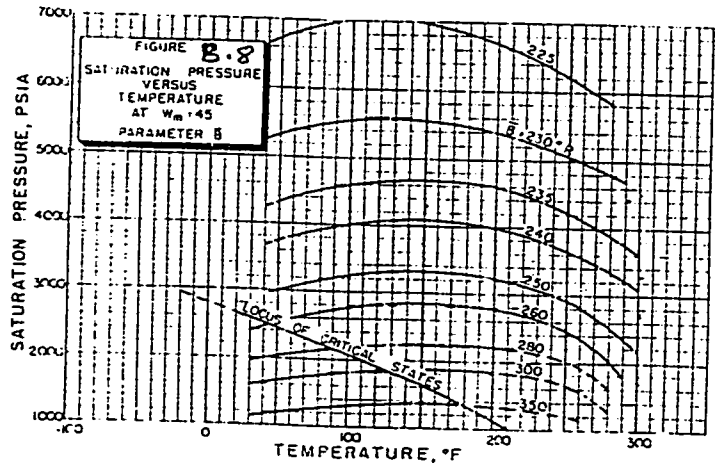

FIG. B.8

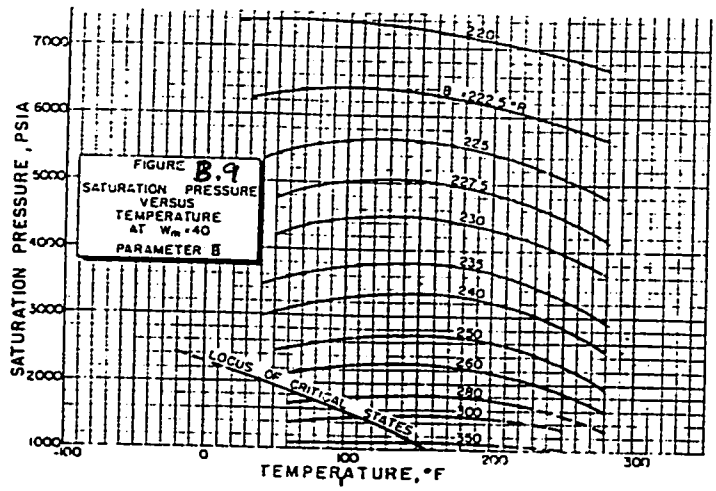

FIG. B.9

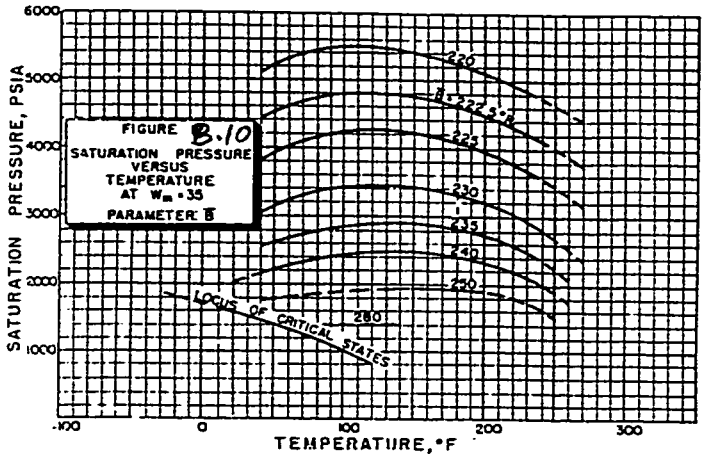

FIG. B.10

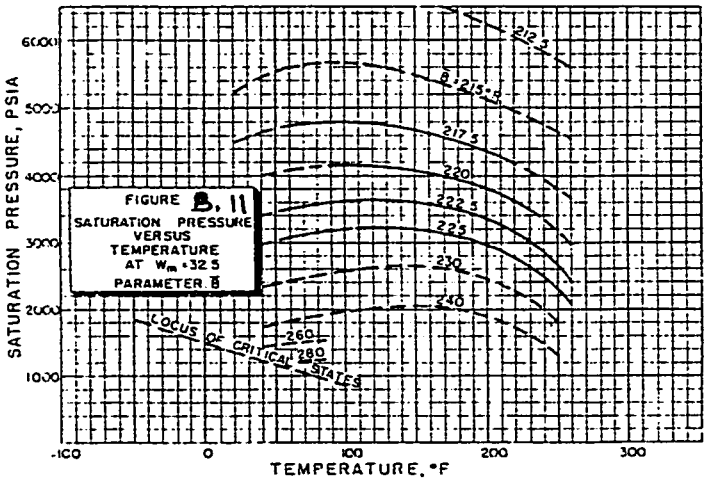

FIG. B.11

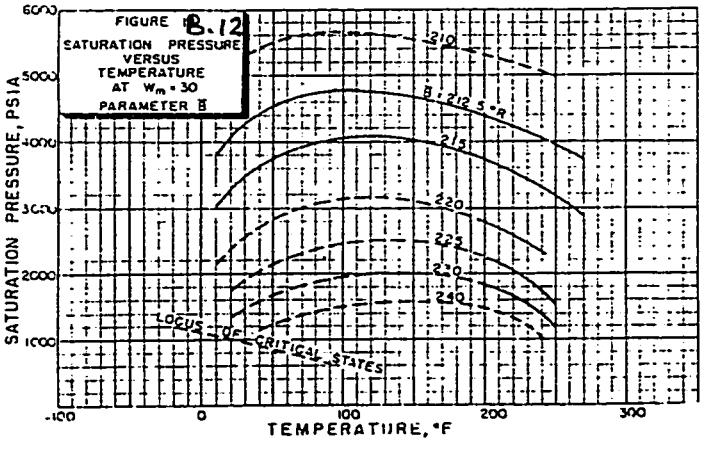

FIG. B.12

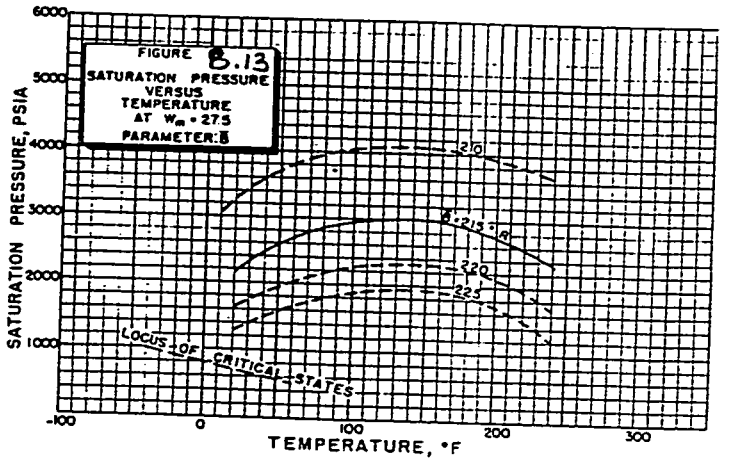

FIG. B.13

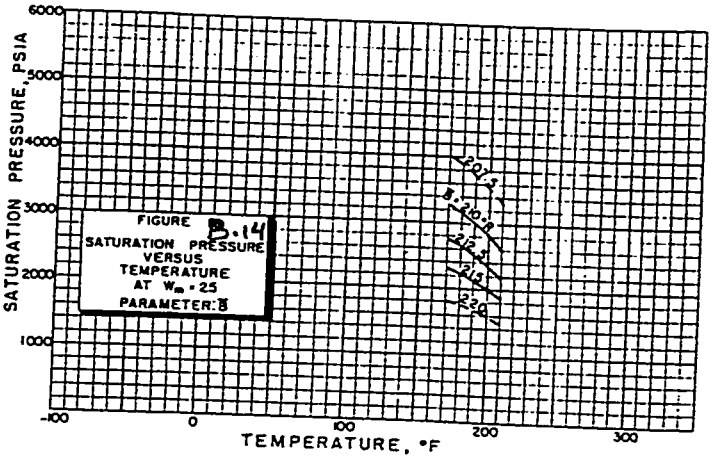

FIG. B.14

Table B.1: Chemical composition of the well stream. [5]

Well Stream Composition

Component	Molecular Weight	Separator Gas Wt. Fraction	Separator Liquid Wt. Fraction	Well Stream Weight Fraction	Well Stream Mol Fraction
CO_2	44	.0145	.....	.0134	.0059
N_2	28	.0334	.. .	.0316	.0218
C_1	16.04	.7910	.0155	.7313	.8860
C_2	30.07	.0762	.0096	.0713	.0460
C_3	44.09	.0317	.0164	.0306	.0134
$i\text{-}C_4$	58.12	.0137	.0114	.0135	.0045
$n\text{-}C_4$	58.12	.0137	.0217	.0144	.0048
$i\text{-}C_5$	72.15	.0075	.0348	.0097	.0026
$n\text{-}C_5$	72.15	.0068	.0221	.0078	.0021
C_6's	86.17	.0090	.1078	.0164	.0037
C_7+*	114	.0025	....	.0018	.0003
C_7+**	139	.....	.7607	.0582	.0081

*Separator Gas
**Separator Liquid

ASTM Distillation of C_7+ from Separator Liquid
Gravity: 56.3° API; 0.7535 g/ml
Distillation

I.B.P.	216°F
10%	232
20%	245
30%	260
40%	289
50%	313
60%	349
70%	383
80%	416
90%	497
95%	
End Point	

Remarks: 10 – 90 Slope = 3.31
Volumetric Average B. Pt. = 337°F

Solution:

Step 1: Calculate the $\overline{B}$ and W_m properties of the heavy ends if the ASTM Distillation of C_{7+} from the separator liquid is available, See Table B.2.

Note: If the properties (specific gravity and molecular weight) of the C_{7+} from the separator liquid are known, then equation A.10 (Whitson) can be used to estimate the boiling point of C_{7+} with a reasonable accuracy. The calculated $\overline{B}$ for the C_{7+} using Eq. A.10 is 785 °R, which is very comparable to 775 °R as calculated in Table B.2.

Step 2: Calculate the values of $\overline{B}$ and W_m for the wellstream composition, as shown in Table B.3. For this example $\overline{B}$ = 219.8 °R and $W_m = 29.4$.

Step 3: Select the proper chart that is the closest to the computed value of W_m. Then, read the saturation pressure at the specified temperature. In the present case the saturation pressure is interpolated between Figure B.12 and B.13. At a temperature of 199°F and at $\overline{B}$ = 219.8 °R, the saturation pressure read

Table B.2: Calculation of $\overline{B}$ and W_m of the heptanes and heavier fractions of the separator liquid. [5]

Cut No.	ml	Mid-boiling Pt., °F	Mid-boiling Pt., °R	Density, g/ml	Wt, g	Wt Fraction of Separator Liquid, g x .7607 / 75.35	Cumulative Wt Fraction of Separator Liquid	Avg. Cumulative Wt Fraction of Separator Liquid	Equivalent Molecular Wt.	g x Equivalent Molecular Wt.	Actual Molecular Wt.	mols = g / Mol. Wt.	mols x Boiling Pt., °R
1	2	3	4	5	6	7	8	9	10	11	12	13	14
							.2393						
1	10	223	683	.716	7.16	.0723	.3116	.2755	103	737	106	.0675	46.1
2	10	239	699	.721	7.21	.0728	.3844	.3480	109	786	110	.0655	45.8
3	10	255	715	.727	7.27	.0734	.4578	.4211	112	814	115	.0632	45.2
4	10	275	735	.734	7.34	.0741	.5319	.4949	119	873	122	.0602	44.2
5	10	300	760	.743	7.43	.0750	.6069	.5694	127	944	131	.0567	43.1
6	10	330	790	.752	7.52	.0759	.6828	.6449	137	1030	141	.0533	42.1
7	10	366	836	.764	7.64	.0771	.7599	.7214	150	1146	155	.0493	41.2
8	10	406	866	.776	7.76	.0783	.8382	.7991	168	1304	172	.0451	39.1
9	10	458	918	.790	7.90	.0798	.9180	.8781	191	1509	195	.0405	37.2
10(rcs)	10	(480)	(940)	(.797)	(7.97)	.0805	.9985	.9583	200	1594	207	.0385	36.2
	Total				75.20					10737		.5398	420.2

$$W_m = \frac{10737}{75.20} = 142.8$$

$$\text{Mol Wt} = \frac{75.20}{.5398} = 139.3$$

$$\overline{B} = \frac{420.2}{.5398} = 778°R$$

Table B.3: Calculation of $\overline{B}$ and W_m for the wellstream analysis.[5]

Component	1 Mol Fraction	2 Boiling Point, °R	3 Mol Frac. x Boiling Point, °R	4 Weight Fraction	5 Equiv. Mol. Wt.	6 Wt. Frac. x Equiv. Mol. Wt.
CO_2	.0059	350	2.06	.0134	44	.59
N_2	.0218	139	3.03	.0316	28	.88
C_1	.8860	201	178.09	.7313	16.04	11.73
C_2	.0460	332	15.27	.0713	30.1	2.15
C_3	.0134	416	5.57	.0306	44.1	1.35
iC_4	.0045	471	2.12	.0135	54.5	.74
nC_4	.0048	491	2.36	.0144	58.1	.84
iC_5	.0026	542	1.41	.0097	69	.67
nC_5	.0021	557	1.17	.0078	72.2	.56
C_6's	.0037	600	2.22	.0164	85	1.39
C_7+ Sep. gas	.0003	718	.22	.0018	114	.21
C_7+ Sep. liq.	.0081	778*	6.30	.0582	142.8*	8.31
			$\overline{B} = 219.8°R$			$W_m = 29.4$

*Computed in Table 8.2

from Figure B.12 2,860 psia, while from Figure B.13 it is 2,150 psia. The interpolated value for $W_m = 29.4$, therefore, is about 2,690 psia. This retrograde dewpoint pressure compares well with the experimental value, which is 2,760 psia.

Appendix C

New Correlation Sample Calculation

Estimate the dewpoint pressure for a well gas-condensate effluent having the following composition and production data?

Component	Mole %
N_2	10.51
CO_2	1.71
H_2S	2.28
C_1	68.44
C_2	6.68
C_3	3.01
i-C_4	0.58
n-C_4	1.21
i-C_5	0.46
n-C_5	0.52
C_6	0.67
C_{7+}	3.93

Reservoir Pressure	7630 psia
Reservoir temperature	282°F
Separator pressure	795 psia
Separator temperature	110°F
R_{SP}	13,000 scf/SP bbl
M_{C7+}	144
γ_{C7+}	0.7923
γ_{gSP}	0.7399

Solution:

Method 1: (for known gas-condensate fluid composition):

1. Calculate the pseudocritical pressure and temperature of the system from equations A.1 and A.2 using the composition and the critical properties given in Appendix D. Use equations A.8 to A.10 to estimate the pseudocritical properties for heptanes-plus.

   $P_{pc} = 639.8$ psia $T_{pc} = 404.9°R$

2. Calculate the pseudoreduced pressure and temperature relative to reservoir pressure and temperature using equations A.3 and A.4.

   $P_{pr} = 11.926$ $T_{pr} = 1.833$

3. Use the new model, given in equation 5.6, to predict the dewpoint pressure.

   $P_d = 5188$ psia

   The experimental dewpoint pressure = 5354 psia.

For this illustrative example, the comparison of the model estimated to the experimental values resulted in a relative error of 3.1%.

Method 2: (Assume the fluid composition is unknown, and the reservoir gas specific gravity is available):

For this gas-condensate system, the reservoir gas specific gravity;

$$\gamma_{gR} = 0.9218$$

1. Use the new pseudocritical correlation (equations 5.8 & 5.9) to estimate the pseudocritical pressure and temperature based on the available reservoir gas reservoir gravity.

$$P_{pc} = 643.5 \text{ psia} \qquad T_{pc} = 405.5^{\circ}R$$

2. Calculate the pseudoreduced pressure and temperature relative to reservoir pressure and temperature using equation A.3 and A.4.

$$P_{pr} = 11.857 \qquad T_{pr} = 1.83$$

3. Use the new model, given in equation 5.6, to predict the dewpoint pressure;

$$P_d = 5158 \text{ psia}$$

The relative error of the predicted dewpoint pressure is 3.7%.

Appendix D

Physical Properties of Gas-condensate Defined Components [2]

Comp.	MW	Critical Pressure, psia	Critical Temp., °R	Boiling Point, °R
N_2	28.013	493	227.27	139.55
CO_2	44.010	1071	547.57	350.74
H_2S	34.080	1300	672.45	383.50
C_1	16.043	667.8	343.04	201.27
C_2	30.070	707.8	549.76	332.51
C_3	44.097	616.3	665.68	416.25
i-C_4	58.124	529.1	734.65	470.78
n-C_4	58.124	550.7	765.32	490.08
i-C_5	72.151	490.4	828.77	542.12
n-C_5	72.151	488.6	845.37	556.92
C_6	86.178	436.9	913.37	615.72

NOMENCLATURE

NOMENCLATURE

Symbol	Description
A	sum of the mole fraction of H_2S and CO_2 in the gas mixture
B	mole fraction of H_2S in the gas mixture
E_a	average absolute percent relative error
E_i	percent relative error
E_r	average percent relative error
E_{min}	minimum absolute percent relative error
E_{max}	maximum absolute percent relative error
E_{rms}	percent root mean square error
G_{pa}	additional gas production (scf/STB) times specific gravity
M_{C7+}	the molecular weight of heptanes plus
M_a	apparent molecular weight of the gas mixture
M_i	molecular weight of the ith component in the mixture
M_o	molecular weight of the tank oil (condensate)
n_d	number of data points
n	number of variables
P_d	dewpoint pressure, psia
P_{pc}	pseudocritical pressure, psia
P_{ci}	critical pressure of component i

P_{pr}	pseudoreduced pressure of the gas mixture
P_{pc}'	pseudocritical pressure, psia, adjusted for nonhydrocarbon
P_{SP}	primary separator pressure (psig)
R	surface producing gas-oil ratio, scf/STB
R_m	mass gas-oil ratio, defined by Eq. 6.3
R_{SP}	producing gas-oil ratio from primary separator (scf/STB)
r^2	coefficient of determination
r	correlation coefficient
s	standard deviation
T	temperature, °R
T_B	heptanes plus boiling point
T_{ci}	critical temperature of component i
T_{pc}	pseudocritical temperature, °R
T_{pc}'	pseudocritical temperature, °R, adjusted for nonhydrocarbon
T_{pr}	pseudoreduced temperature of the gas mixture
T_{SP}	primary separator temperature (°R)
T_R	reservoir temperature (°R)
V_{eq}	vapor equivalent of primary separator liquid (scf/STB)
y_i	mole fraction of component i in the gas mixture
y_{Ci}	mole fraction of component C_i in gas mixture
γ_{C7+}	specific gravity of heptanes-plus fraction (water = 1.0)
γ_{gs}	average specific gravity of surface separator (s) gas (air = 1.0)

γ_o	stock-tank oil specific gravity (water = 1.0)
γ_{gR}	reservoir gas specific gravity (air = 1.0)
γ_{gSP}	specific gravity of gas from primary separator (air = 1.0)

Subscript

SP	primary separator
R	reservoir
g	gas
o	tank oil
C1,C2,...	methane, ethane,...
C7+	property of heptanes plus fraction
a	apparent, or average
m	mass
r	relative
eq	equivalent
pa	additional gas production
d	dewpoint
rms	root mean square
API	API gravity
pc	pseudocritical
pr	pseudoreduced

REFERENCES

REFERENCES

1. Bradley, H.B.: Petroleum Engineering Handbook, SPE, Richardson (1987), Chapters 21,23,39.

2. McCain, W.D.: The Properties of Petroleum Fluids, Penn Well Publishing Company: Tulsa, 1990.

3. Sage, B.H. and Olds, R.H.: "Volumetric Behavior of Oil and Gas from Several San Joaquin Valley Fields," Trans., AIME (1947) Vol. 170, 156-173.

4. Reamer, H.H. and Sage, B.H.: "Volumetric Behavior of Oil and Gas from a Louisiana Field," Trans., AIME (1950) Vol. 189, 261-268.

5. Organick, E.I. and Golding, B.H.: "Prediction of Saturation Pressures for Condensate-Gas and Volatile-Oil Mixtures," Trans., AIME (1952) Vol. 195, 135-148.

6. Nemeth, L.K. and Kennedy, H.T.: "A Correlation of Dewpoint Pressure With Fluid Composition and Temperature," paper SPE 1477 presented at SPE 41st Annual Fall Meeting held in Dallas, Tex., 1966.

7. Potsch, K.T. and Braeuer, L., "A Novel Graphical Method for Determining Dewpoint Pressures of Gas Condensates," Paper SPE 36919, presented at the 1996 SPE European Conference held in Italy, October 22-24, 1996.

8. Ahmed, T.: Hydrocarbon Phase Behavior, Vol. 7, Gulf Publishing Company: Houston, 1989.

9. Eilerts, C. K. et al.: "Phase Relations of Gas Condensate Fluids," Monograph 10, USBM (1957) Vol. I.

10. Wichert, E. and Aziz, K., "Correlations of Z's for Sour Gases," Hydrocarbon Processing, Vol. 51, No. 5, 1972, pp. 119-122.

11. Sutton, R.P., "Compressibility Factors of High-Molecular-Weight Reservoir Gases," Paper SPE 14265, presented at the 1985 SPE Annual Technical Conference and Exhibition, Las Vegas, Sept. 22-25, 1985.

12. Moses, P.L., "Engineering Applications of Phase Behavior of Crude Oil and Condensate Systems," JPT (July 1986) 715-23.

13. Pederson, K.S. et al.: Properties of Oils and Natural Gases, Vol. 5, Gulf Publishing Company: Houston, 1989.

14. Rays, D.G. et al., "Two-Phase Compressibility Factors for Retrograde Gases," SPE Formation Evaluation (March 1992) 87-92.

15. McCain, W.D., "Reservoir-Fluid Property Correlations-State of the Art," SPE Reservoir Engineering (May 1991) 266-272.

16. McCain, W.D., "An Improved Method for the Determination of the Reservoir-Gas Specific Gravity for Retrograde Gases," JPT (July 1989) 747-52.

17. Whitson, C.H. and Torp, S.B., "Evaluating Constant Volume Depletion data," JPT (March 1984) 610-20.

18. SAS User's Guide: Statistics, SAS Institute Inc., Cary, North Carolina, 1982.

19. Devore, J. and Peck, R.: Statistics, The Exploration and Analysis of Data, Brooks/Cole Publishing Co.: USA, 1997.

20. Younger, M.S.: Handbook for Linear Regression, Wadsworth, Inc., Belmont: USA, 1979.